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A STUDY ON FATIGUE LIFE OF MARINE VERTICAL PROPULSION SYSTEM

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Keyword: Vertical Propeller (VSP), Horizontal Circulation Model Basin, ANSYS Numerical Simulation

ABSTRACT

In this study, the horizontal circulation model basin is utilized to simulate the force on the Voith 21gs-mc-1600 vertical propeller in the water, followed by calculating the possible failure time of the blade due to metal fatigue by means of ANSYS numerical simulation. The results show that the metal fatigue of the Voith 21gs-mc-1600 vertical propeller grows non-linearly when the ship is travelling above the economic speed. Only travelling at all speed evenly can maintain the service life of the ship for more than 30 years. This can be used as investing and planning reference when the ship comes to the end service life.

INTRODUCTION

Owing to the geological location, shipbuilding industry plays a vital role to domestic economics in Taiwan. Shipbuilding and maintenance are both time consuming and costly. In addition, it is not applicable to replace shaft system assembly due to issues regarding ship load balance and main engine integration. Therefore, effective evaluation on the service life is critical.

1. Incentive and Purpose

The ship's propulsion system is a key factor for maritime safety. Most of the equipment can be repaired immediately through scheduled maintenance, assembly replacement, performance upgrade etc. However, being submerged in sea water, the condition of propellers is difficult to identify. This research utilizes the horizontal circulation model basin to simulate the im-pact force of the vertical blades when in operation and the ANSYS numerical simulation to analyze the metal characteristics, stress, fatigue, and rotational torque to determine the key observation and replacement cycle of the vertical propeller, providing the owner's future investment reference. The VSP systems are current used on USN Osprey class, ROCN YongFen mine hunting crafts, 5400 HP Tugboats of Jong Shyn Shipbuilding cooperation.

Based on actual serving record, the design speed is less than 7 knots at speed order of AH 7. The actual GPS speed is usually less than 4 knots when sailing at sea due to sea states. The speed order AH 7 is not frequently used and only used during entering/leaving ports. The follow on study analyzes the service life of speed order above AH 7. This leads to restrictions of this study.

1.1 Research process

A single ship type is used as a study case in this re-search, and the best operation and maintenance plan of the ship is determined by experiment and numerical simulation respectively. (The research flow chart is shown in Fig. 1)

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The study begins by defining the incentive and goal, which is investing impacts on ship propeller as a reference for future investment. The VSP propeller is selected as study case and analysis is done by operating in a ship model basin. After model basin experiment, the data is input into ANSYS for simulation. An analysis is done by the results, and it shows impact on the propeller based on different criteria. Eventually, a conclusion is drawn and provides users as well as owners with a reference for how to operate to best preserve the ship and a time frame for owner's investment considerations.

Study Case

The vertical propeller, also known as Voith Schneider Propeller (VSP), is a new generational ship propulsion system. The case used in this study is a propulsion system incorporating diesel engines powered by the Italian ISOTTA FRASHINI ID36SS8V-AM connecting the main reducing gear by a shaft to drive Voith 21gs-mc-1600 vertical propeller (as shown in Fig. 2), the blades are made of Inconel. The speed of the propeller can be driven by the main engine to ahead one (AH 1), ahead two (AH 2), ……, ahead ten (AH 10), with the speed from 58 to 87 rpm, and the operating hours are approximately 135 days per year.

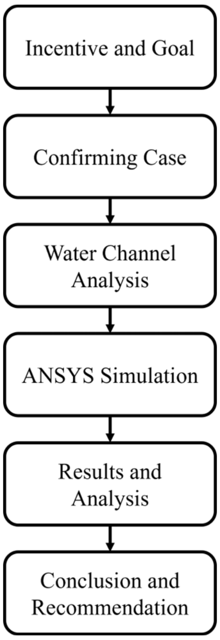


Fig. 1 Research flow chart

1. Literature Review

According to the US Navy Technical Manual S9245-BM-MMA-10 PORPELLER, CYCLOIDAL PITCH MODEL 21GS-MC-1600, the effective sweeping area of the VSP is the rectangular area defined by the diameter of the rotary track of each vane and the length of the vane. The available space within this effective sweeping area is considerably larger than that of conventional propeller blades[1]. It can be seen that under the same environmental factors, the VSP vane is greatly affected by the force due to larger surface, and this accelerates the occurrence time of metal fatigue. However, there is no research on the service life of VSP in Chinese and foreign literature. In addition, referring to the experience of domestic shipyards and the current situation of the domestic shipbuilding industry, the relevant data are commercial secrets and can only be simulated and analyzed in the shipyard before ship repairs. The case of this study is not made domestically; however, the life cycle and maintenance policy must be considered for the maintenance. Referring to the model basin experiment simulation scenarios and ANSYS numerical simulation application, the research and development trends are listed as follows:

Model basin experiments for ships:

1. Lin, J. (2012) Research on numerical wave-making water channels and numerical simulation of ocean platforms motions in waves pointed out that various results of interaction between ocean platforms and waves can be observed through simulated scenarios, which can not only effectively save time and cost, but also accurately calculate various numerical values, and thus provide accurate numerical simulation results for ship design [2].

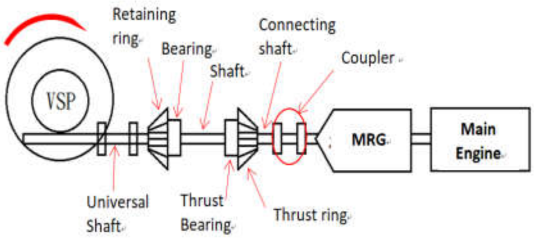


Fig. 2 VSP operating with engine

2. Hsiao Y. (2019) In the parameter design of resistance and configuration of small surface platform, it is pointed out that resistance found on the surface platform made of smaller scale, the environment parameter of the ocean simulated by the circular channel, and under various environmental factors can provide reference for subsequent ship propulsion power application and shipbuilding application [3].

Applying ANSYS numerical simulation to metal fatigue and service life:

1. Shen Y. (2016) In the fatigue test of aluminum alloys, a mockup is manufactured according to the case's shapes, incorporating ANSYS numerical simulation with actual boundary condition setting to test the fatigue limit of the welding area. The crack of the material will be observed to confirm the precision of ANSYS simulation result [4].
2. Tsao F. (2013) In the analysis of vibration im-pact to service life of rubber metal materials, the fatigue occurs with time gradually and there won't be a sudden destruction [5].
3. Huang L. (2021) In a motorcycle motion simulation and the parts fatigue analysis, ANSYS Workbench was used to pro-vide optimizing recommendation based on fatigue hours estimated. The total weight was reduced by 0.78 kg, which is about 5.346% of total weight. The fatigue damage can remain within 75%, which meets the safety factor [6]

Applying ANSYS numerical simulation to actual ships:

1. Wu Y. (2018) A small-scaled model is used to test and simulate propulsion system of a naval ship. Numerical simulation analysis is done by ANSYS Workbench finite element mathematical analysis and the result was verified non-destructive testing to check the accuracy of estimated fatigue hours. The crack occurred at the end of the shaft. The result provided user with recommendations to operate the ships [7].
2. Shen H. (2019) ANSYS Workbench 18.0 software static structure simulation analysis is carried out for the naval ship's fin stabilizer shaft bushing. The bushing is analyzed in two different setting, clean bushing and bushing with marine growth, rotating at 1RPM, and the outer wall is under force of 500N and 700N. ANSYS Workbench 18.0 is used to carry out different force analysis on the outer wall, and results showed that the stress and strain are easily to concentrate on area with marine growth, and thus determine the cause of the bushing damage in sea water [8].

2. Model basin experiments for ships: Horizontal circulation model basin

In order to make the subsequent numerical simulations in line with the current situation, the VSP model is made of pure copper at the scale of 1:100, combined with the possible speed used at sea. The actual sailing condition is simulated in the model basin, and the possible forces on the VSP under various ship operations are obtained by experiment.

2.1 Characteristic of the model basin

The size of the model basin used in this experiment has a length of 14 m, a width of 5.325 m, a height of 2.2 m, and a capacity of 80 tons. The test section has a length of 5.5 m, a width of 1.5 m, a height of 1.1 m, and a capacity of 80 tons. It is driven by an axial motor to produce 0.2-2.0 m/ s water flow, which corresponds to the sea surface situation. Therefore, the VSP condition with various forces under water can be observed stably for a long time (the schematic diagram of the model basin is shown in Fig. 3).

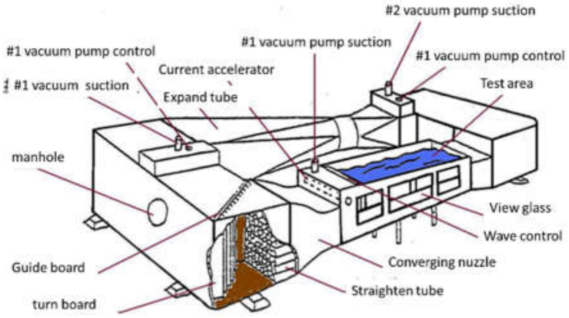


Fig. 3 Schematic diagram ship model basin

2.2 Current speed meter installation

The flow rate is measured with a Swoffer 2100 current speed meter (as shown in Fig. 4). The meter is powered by a single 9-volt battery and connected to a 1.4 m long connecting rod (as shown in Fig. 5), so the flow rate can be measured at the water depth of 1.4 m. A 5 cm diameter propeller is attached to the other end of the connecting rod. The rotational speed measured by the propeller in the tank will be transmitted to the meter. After the meter's calculation and processing, the speed will be displayed by a digital display. The measurement range of the Swoffer 2100 current speedometer is 0.03~7.5 m/s.

2.3 Design of model basin experiment

In this experiment, the 1:100 VSP model is used in the circulation basin and water flow is generated by adjusting the motor power to simulate the relative velocity of the actual ship speed when the VSP is in a stable sea state, for the purpose of setting the flow velocity to impact the propeller model. The tank cur-rent values are based on actual current obtained by speed log of the ship. After the meter confirms that the water flow reaches the set flow rate, record the impact force of each blade after running at each speed.

Fig. 4 Current speed meter

Fig. 5 Connecting rod

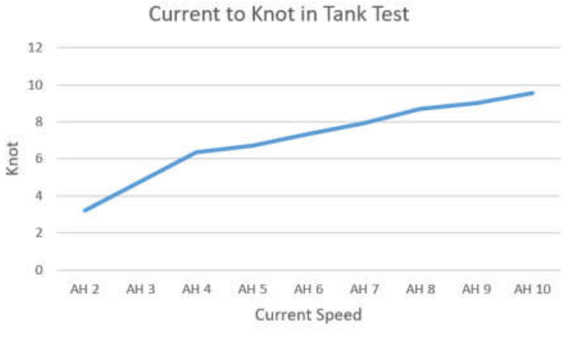
2.4 ANSYS simulation and finite element analysis

The powerful auxiliary calculation software of the ANSYS system uses structural finite elements to complete the whole process from structural modeling to meshing, solution setting, simulation calculation, post-processing, and optimization design. The use of 3D modeling can both linearly and non-linearly simulate pre-stress mode, harmonics, spectral response, and random vibration etc. Pre-processing, analysis and calculation, and post-processing are composed of three modules. The GUI (Graphical User Interface) operation interface combines the functions of the main menu, toolbox, project window, message window, progress window, and status bar. Through various integration and application calculation methods, the model interface performance is close to simulation.

The division of a single structure is called an element, and it is realized by a specific spatial discretization of the spatial dimension, which is realized by constructing a grid of objects: the numerical domain of the solution has a finite number of points. The finite element method formulation of the boundary value problem finally forms a set of algebraic equations. The simple equations that model these finite elements are then combined into a larger system of equations that model

Table 1 Current to knot setup

Knot to current	
Knot	Tank current (m/s)
AH 2	3.188746543
AH 3	4.783074815
AH 4	6.377433087
AH 5	6.707300315
AH 6	7.367034773
AH 7	7.916813487
AH 8	8.686503684
AH 9	9.016370916
AH 10	9.56614963



the entire problem. The finite element method uses the mutation method from the mutation calculus to approximate the results by minimizing the associated error function. The results represent the structural forces and serve as references for modifying follow-up design and predicting service life. Therefore, the recommended maintenance schedule can be determined and the end-user will be able to manage service costs effectively.

2.5 3D model setup and meshing

The Voith 21 gs-mc-1600 vertical propeller system is equipped with five blades and driven by the main engine. The computer calculates the flow direction and the flow rate to control the propeller's steering and rotation speed making the ship possible to steer 360 degrees, and the maximum speed is 10 knots. SolidWorks 2021 is used to create 3D VSP model drawing, and then transfer the VSP drawing file to ANSYS Workbench to create a 3D shaft system model (as shown in Fig. 6).

There are 3 types of ANSYS fine mesh analysis, which are automatic grid, tetrahedron and hexahedron unstructured grid (as shown in Fig. 7). The hexahedron grid mesh analysis is selected for the VSP model. Through the software, it is found that the height of the sleeve mold is 2,441.2 mm, the diameter of the horizontal disk is 3,305.9 mm, the number of nodes is 143,050, and the number of grids is 78,873 (the ANSYS system model is shown in Figure 8).

Horizontal Circulation Model Basin Experiment

During the experiment, two support rods were fixed at the front and back of the model, and a load cell was connected to the center of the VSP horizontal disk to obtain the actual impact force in the channel. The schematic diagram is shown in Fig. 9. The upper end of the support rod is fixed above the test area of the channel by a fixing frame. Rail-type sliding frames are installed on both sides of the fixing frame, and ball bearings that can slide smoothly are installed in the sliding way. When the model is subjected to the impulse of the water flow, it can be smoothly driven along the flow direction. Different from towing channel, friction correction can be ignored for circulating

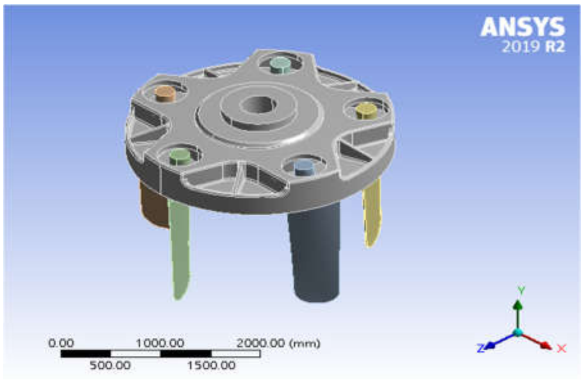


Fig. 6 3D model of VSP

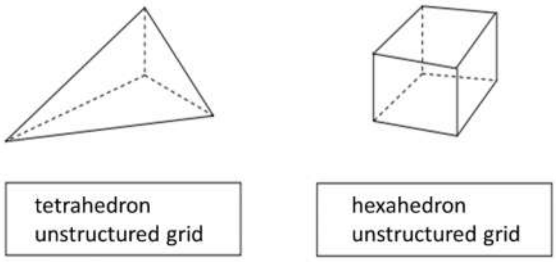


Fig. 7 Tetrahedron and hexahedron unstructured grid

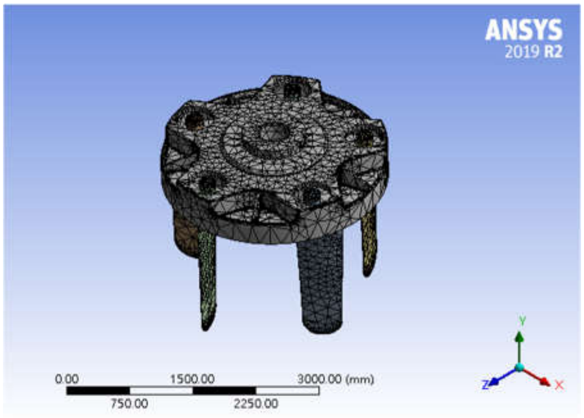


Fig. 8 ANSYS system model

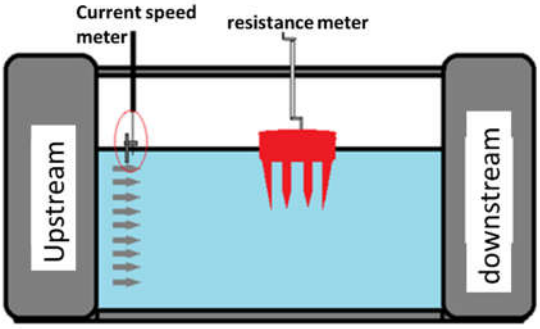


Fig. 9 Schematic diagram of model basin

model basin because the test model remained fixed and the resulted are obtained by relative motions. Observe the force measured on the blades of the model at various speeds. The actual test is shown in Fig. 10 and test results are shown in Fig. 11.

ANSYS Numerical Simulation

1. Simulation Parameter Setting

In this study, the Voith 21gs-mc-1600 vertical propeller is made of Inconel 625. The material parameters of the system database can be selected (as shown in Fig. 12), and the setup is completed based on service cycles of the vertical propeller, alternation stress (Fig. 13) and fatigue curve (Fig. 14) of the material.

2. Nickel-Based Alloy S-N Database Setting

As previously discussed in chapter 1, the vertical propeller is driven by a shat. Therefore, the fixed support is set on the horizontal disk and vertical propeller driven by a shaft was set as the boundary condition. Following simulations are continued according to the speed and the impact force obtained in the experiment. The boundary setting is shown in Fig. 15.

In this study, the VSP rotating speed is 58RPM from AH 1 to AH 4, 61RPM for AH 5, 67RPM for AH 6, 72RPM for AH 7, 79RPM for AH 8, 82RPM for AH 9, and 87RPM for AH 10. The propeller rotation setting is shown in Fig. 16. After experiment of each speed, the average force on the propeller is shown in Table 2, and the force setting by the flow velocity is shown in Fig. 17.

The unit is selected according to the metal fatigue status caused by the actual force on the vertical propeller. The system unit setting can be day, hour, minute, etc. The unit Day is selected because the experimental design requires long-term observation. The fatigue setting parameters are shown in Fig. 18.

3. Numerical Simulation Results

In this study, the Voith 21gs-mc-1600 vertical propeller is made of Inconel 625. The various current speed from AH2 to AH10 are subjected to ANSYS nu-

Fig. 10 Actual test picture

	Speed	Velocity_ inlet(m/s)	RPM	F1	F2	F3	Force (average)
1	AH 2	3.188716543	58	1136.25	1159.47	1152.22	1149.31
2	AH 3	4.783074815	58	7996.21	5005.69	4997.33	4999.74
3	AH 4	6.377433087	58	12988.65	13135.18	13000.85	13041.56
4	AH 5	6.707300315	61	15332.74	14922.13	14526.48	14927.12
5	AH 6	7.367034773	67	17665.91	17958.54	17726.35	17783.6
6	AH 7	7.916813487	72	19121.35	19816.29	20031.54	19656.39
7	AH 8	8.686503687	79	19889.52	24551.16	22003.64	22148.11
8	AH 9	9.016370916	82	23621.36	23479.41	22987.26	23362.68
9	AH 10	9.56614963	87	25006.25	25026.53	25602.94	25211.91

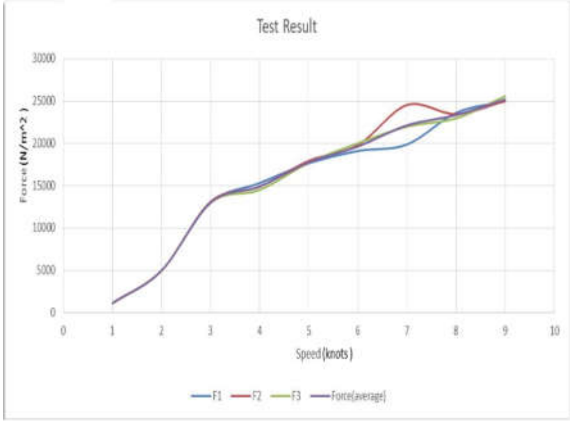
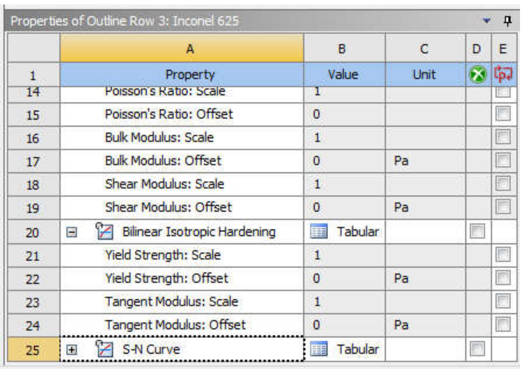


Fig. 11 Test results



	A	B	C	D	E
1	Property	Value	Unit		
14	Poisson's Ratio: Scale	1			☐
15	Poisson's Ratio: Offset	0			☐
16	Bulk Modulus: Scale	1			☐
17	Bulk Modulus: Offset	0	Pa		☐
18	Shear Modulus: Scale	1			☐
19	Shear Modulus: Offset	0	Pa		☐
20	⊟ Bilinear Isotropic Hardening	Tabular		☐	
21	Yield Strength: Scale	1			☐
22	Yield Strength: Offset	0	Pa		☐
23	Tangent Modulus: Scale	1			☐
24	Tangent Modulus: Offset	0	Pa		☐
25	⊞ S-N Curve	Tabular		☐	

Fig. 12 System database material parameters

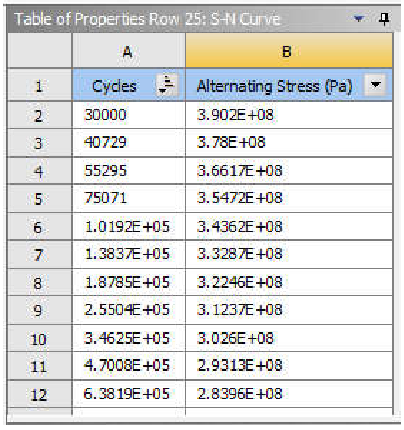


Table of Properties Row 25: S-N Curve

	A	B
1	Cycles	Alternating Stress (Pa)
2	30000	3.902E+08
3	40729	3.78E+08
4	55295	3.6617E+08
5	75071	3.5472E+08
6	1.0192E+05	3.4362E+08
7	1.3837E+05	3.3287E+08
8	1.8785E+05	3.2246E+08
9	2.5504E+05	3.1237E+08
10	3.4625E+05	3.026E+08
11	4.7008E+05	2.9313E+08
12	6.3819E+05	2.8396E+08

Fig. 13 Alternating stress

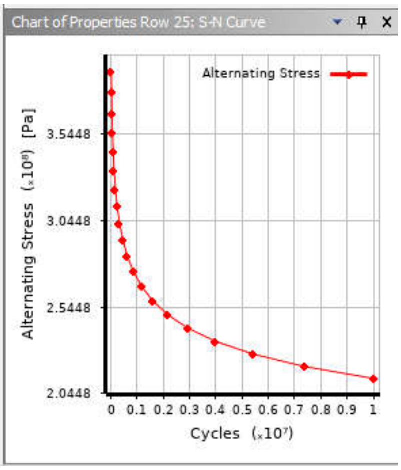
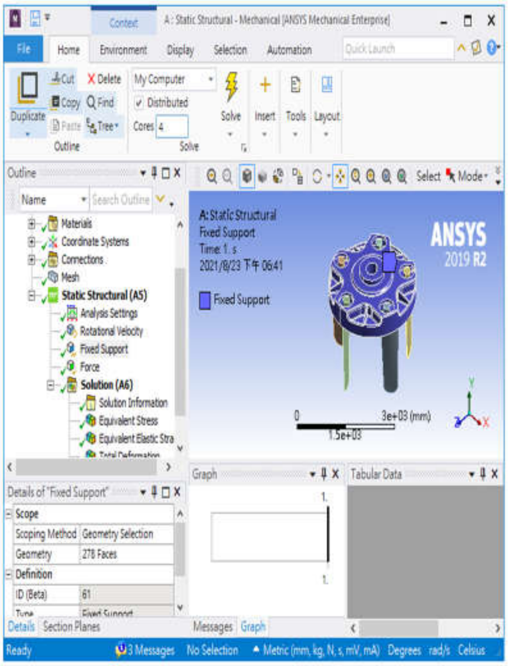


Fig. 14 Alternating stress curve



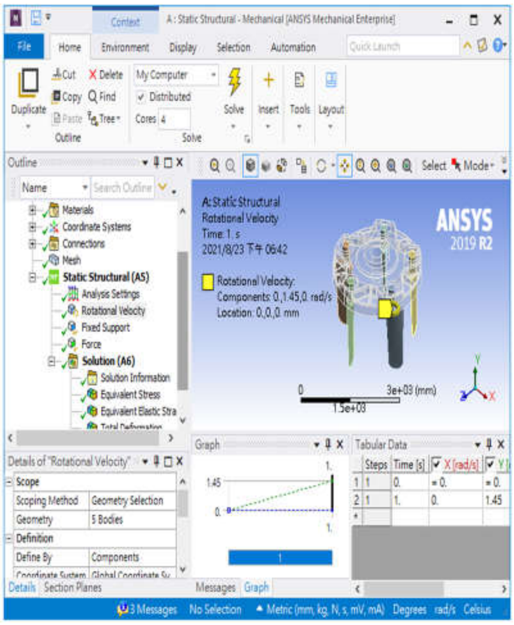
A: Static Structural
Fixed Support
Time: 1. s
2021/8/23 下午 06:41

Fixed Support

Details of "Fixed Support"

Scoping Method	Geometry Selection
Geometry	278 Faces
ID (Beta)	61
Type	Fixed Support

Fig. 15 Boundary setting



A: Static Structural
Rotational Velocity
Time: 1. s
2021/8/23 下午 06:42

Rotational Velocity
Components: 0.,1.45,0. rad/s
Location: 0.,0.,0. mm

Details of "Rotational Velocity"

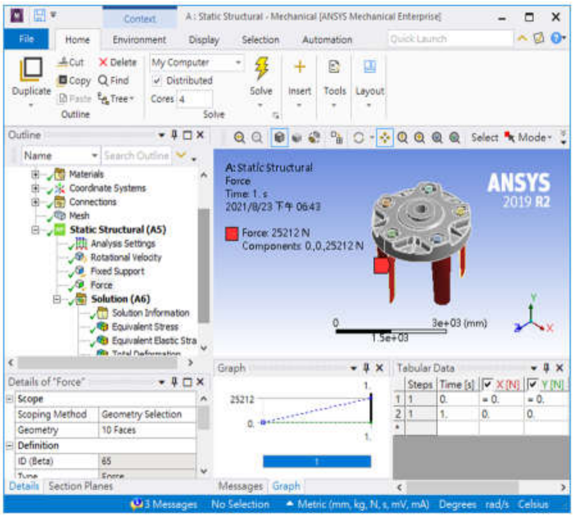
Scoping Method	Geometry Selection
Geometry	5 Bodies
Define By	Components

	Steps	Time [s]	X [rad/s]	Y [rad/s]
1	1	0.	= 0.	= 0.
2	1	1.	0.	1.45

Fig. 16 Propeller rotating setting

Table 2 Average force at each speed

	RPM	Force (N/M2)	Velocity_inlet(M/S)
AH 2	58	2374.69	3.1887
AH 3	58	4999.74	4.783
AH 4	58	13041.56	6.3774
AH 5	61	14927.12	6.707
AH 6	67	17783.6	7.367
AH 7	72	19656.39	7.918
AH 8	79	22148.11	8.686
AH 9	82	23362.68	9.0163
AH 10	87	25211.91	9.5661



A: Static Structural
Force
Time: 1. s
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Force: 25212 N
Components: 0.,0.,25212 N

Details of "Force"

Scoping Method	Geometry Selection
Geometry	10 Faces
ID (Beta)	65
Type	Force

	Steps	Time [s]	X [N]	Y [N]
1	1	0.	= 0.	= 0.
2	1	1.	0.	0.

Fig. 17 Force by current setting

merical simulation. The results are shown from Fig. 19 to Fig. 26. Some environmental parameters are considered, including the rotating speed, direction of rotation, average force, and velocity inlet.

The result shows the velocity inlet increase with the rotating speed, causing the increase of average force and significant reduction of the service life of the VSP propeller. The numerical simulation result is shown in Table 3.

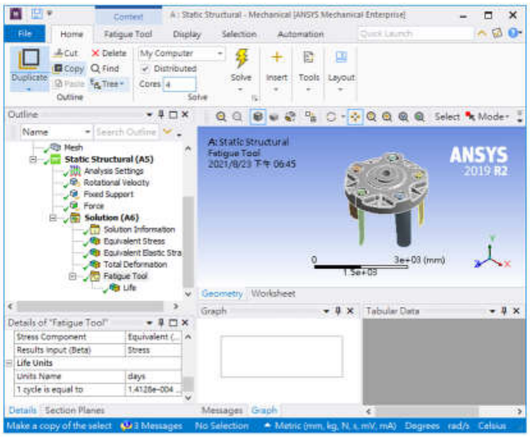
Research Results and Service Life Analysis

The Voith 21 gs-mc-1600 vertical propeller can be used for more than 30 years at the economic speed or above (as shown in Table 4). However, each increase in the speed will reduce the service life significantly caused by the metal fatigue. The speed of AH 7 is not only the economic speed but also most suitable for long-term use. Travelling at high speed for a long time will result in short service life.

The naval warship maintenance strategy is based on the maintenance cycle of 5-6 years (in-dock maintenance). The results of this research show that the fourth maintenance cycle after the ship was built (20-24 years), a detailed inspection of the VSP must be arranged to confirm the operation conditions, the current conditions of equipment and materials. The replacement plan or new build project will be invested in the early stage of metal fatigue to facilitate the sustainable development of the enterprise.

Conclusions and Future Research Directions

In this study, the impact force of the VSP at various speeds was measured by utilizing a 1:100 scale model of the VSP vertical propeller through the horizontal circulation model basin, and then ANSYS numerical simulation design was applied to calculate the possible service life. Conclusions and future research directions are as follows:



Cores 4

Stress Component	Equivalent (...
Results Input (Beta)	Stress
Life Units	
Units Name	days
1 cycle is equal to	1.4126e-004 ...

Fig. 18 Fatigue parameter setting

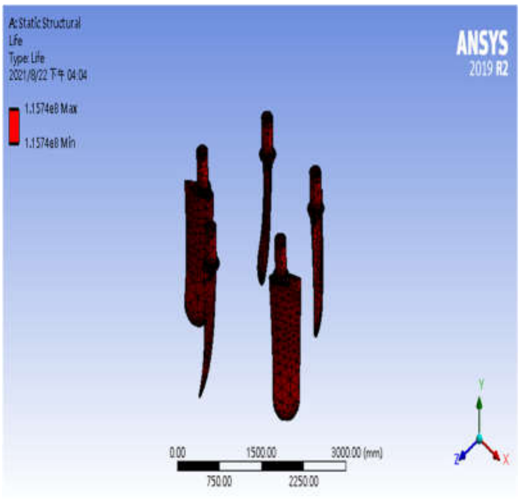


Fig. 19 AH2 service life

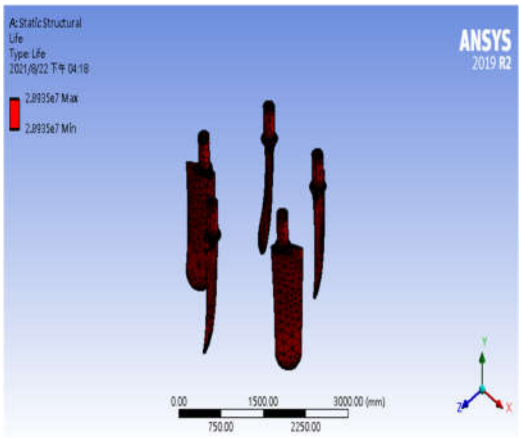


Fig. 20 AH3 service life

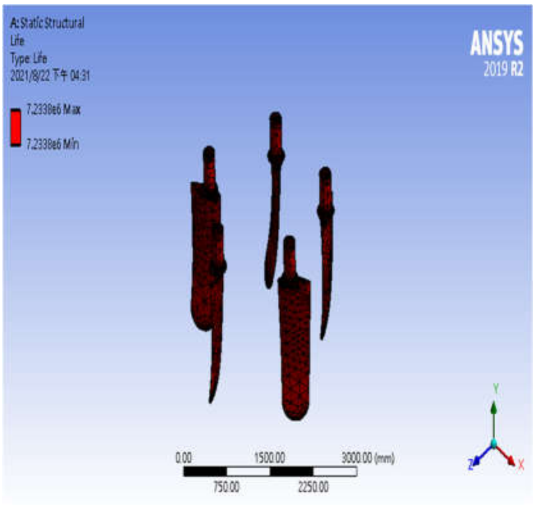


Fig. 21 AH5 service life

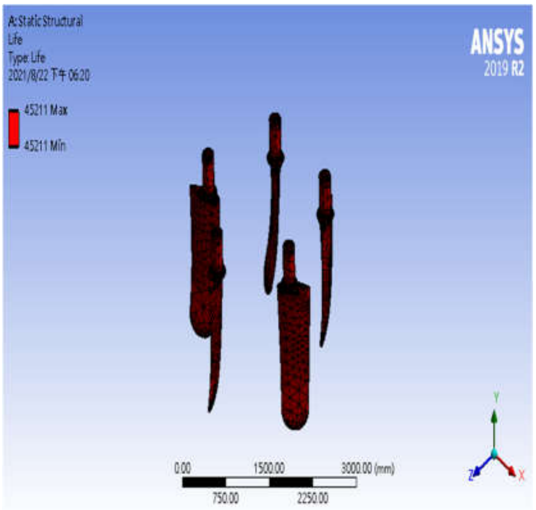


Fig. 22 AH6 service life

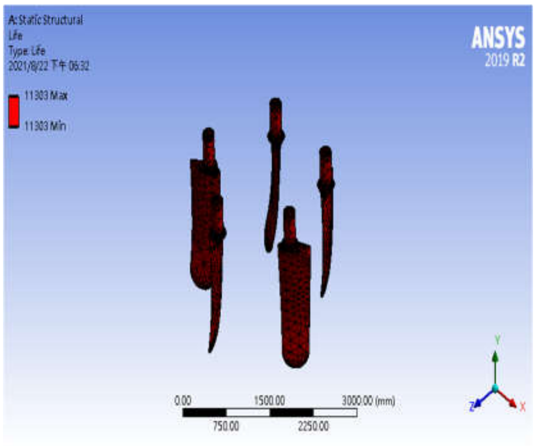


Fig. 23 AH7 service life

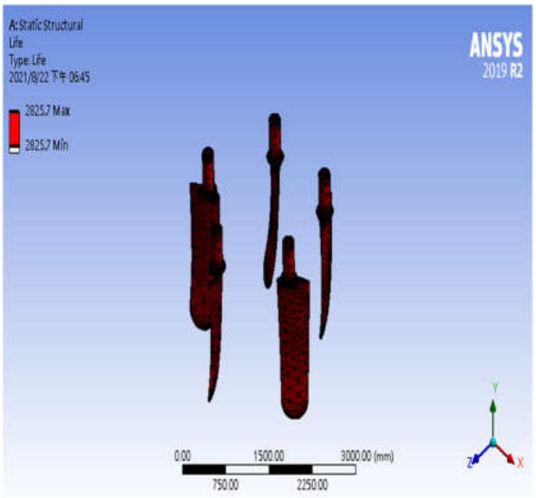


Fig. 24 AH8 service life

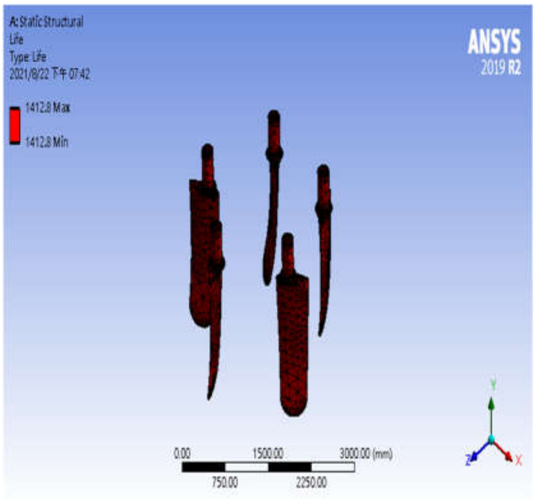


Fig. 25 AH9 service life

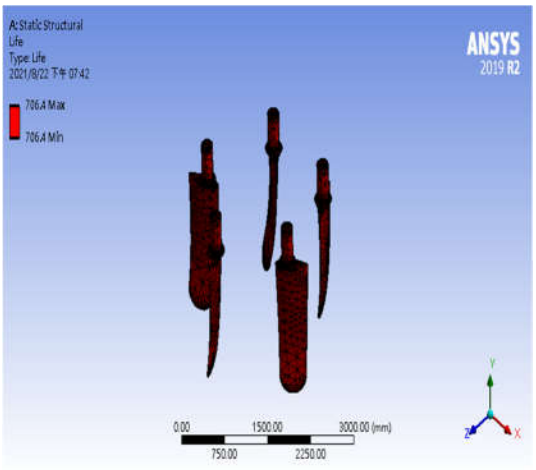


Fig. 26 AH10 service life

1. Numerical simulation is used to determine that the Voith 21 gs-mc-1600 vertical propeller can be used for 30 years at the economic speed and above when evenly operated. It provides an important reference for the owner's cruise planning and the continuation plan of the vessel and the inspection cycle in the dock.
2. This research can be used to expand the database to calculate and evaluate underwater equipment of various types of ship, and further to develop preventive maintenance, maintenance scheduling and logistics parts supply reference. The owner can refer to the estimated failure point to prevent in advance and avoid increasing the risk of storage or contingent maintenance.
3. In terms of future research, the results of this research have found that traveling above the economic speed will result in nonlinear growth in metal fatigue for Voith 21gs-mc-1600 vertical propeller. The service life of the ship can only be maintained for more than 30 years when the speeds are evenly operated. It is recommended to apply neural network to optimize planning for speed, course, and maintenance plan and to maximize the benefits of the enterprise.

Table 3 Numerical simulation result

Speed	RPM	Service life (day)	remark
AH 2	58	1.1574e^8	
AH 3	58	2.8935e^7	
AH 5	61	7.2338e^6	
AH 6	67	45211	
AH 7	72	11303	Econ. speed
AH 8	79	2825.7	
AH 9	82	1412.8	
AH 10	87	706.4	

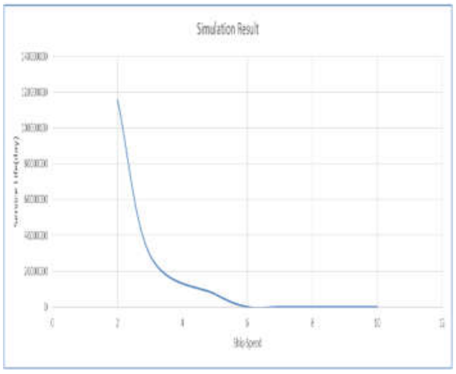


Table 4 Numerical simulation result

Ship Speed	Simulation Service life (day)	Avg. days per year	Safe service life (yr)
AH 7	11303	135	83.7
AH 8	2825.7	135	20.93
AH 9	1412.8	135	10.46
AH 10	706.4	135	5.23
Average			30.08

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船舶垂直推進系統疲勞壽命研究

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關鍵詞：垂直俥葉、水平式環流水槽、 ANSYS 數值模擬

摘 要

本研究針對 Voith 21gs-mc-1600 垂直俥葉採水平式環流水槽，模擬俥葉水中受力情形，再以 ANSYS 數值模擬方式計算俥葉可能金屬疲勞引發故障可能時間。實驗結果顯示，Voith 21gs-mc-1600 垂直俥葉於經濟速率以上行駛對於金屬疲勞產生採非線性成長，採速率平均使用方可維持艦艇 30 年以上壽命，供企業於艦艇壽期末端整體投資規畫參考。

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