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Analysis of the Structural Failure of Marine Propeller Blades

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Abstract

A series of detailed study was performed to identify the sources of the propeller blade failure and resolve the problem systematically, by use of the theoretical tools and by the direct measurement and observation in the full-scale sea trials. The selection of inexperienced propulsion control system with a reversible gear system is shown to cause the serious damage to the propeller blades in crash astern maneuver, when the rotational direction of the propeller is changed rapidly. Quasi-steady analysis for propeller blade strength using FEM code in bollard backing condition indicates that the safety factor should be order of 18 $\sim$ 20 to avoid the structural failure for the selected propeller geometry and reduction gear system.

Keywords: propeller blade failure, sea trial, crash astern, crash ahead, OCS, MTC, MTRC, GCS, proSTEC

1 Introduction

Blade damages on marine propellers are mostly caused by the collision with floating objects, cavitation erosion or material impurities. With the development of high performance engines and new reduction gear systems together with increase of the blade skew angle, the blade strength is relatively weakened, being exposed to the unprecedented mechanical problems and hydrodynamic loadings.

The vessel taken in the present study is a landing ship tank(LST), built for a navy in a shipyard in Korea, with the target objective of a good landing and retreating ability on the shore requiring a good astern performance. The vessel was designed and constructed based on the parent ship, following the US military specifications(1982) and rules of various Classification Societies including Korean Register(KR), Lloyd, ABS and DnV. The unsteady lifting-surface propeller code of Kerwin and Lee(1976) and the design code of Kim et al(1995) has been used to reduce the vibration level with the introduction of the skew angle of 25 degrees.

During the sea trial tests, the new reduction gear system and the skewed blades were damaged one after another. The present study aims to give full illustration of the procedure to locate the trouble sources and to resolve the problems systematically. The study will contain the details of the consecutive trial tests, the propulsion system and the propeller blade strength analysis, providing information on the related performances of the parent ship.

2 Propeller design

Three propellers were designed consecutively to have the good performance in subcavitating operation range with the traditional NACA a=0.8 mean line and NACA 66 thickness form using the lifting-surface design code. The first design propeller, P1, has a skew angle extent of 25 degrees with an aim to decrease the vibration level. The propeller P1 showed a good speed performance, but could not avoid the blade damages(the tip bending and crack near the trailing edge) during the crash astern trials. The blade failure forced the reduction of the skew angle to 15 degrees and the increase of the thickness in the design of the second propeller, P2. Based on the performance of P2, the third propeller, P3, was designed for the final acceptance trials with additional reduction of skew angle extent of 8.7 degrees. Table 1 and Figure 1 show the particulars of three propellers and the outline of all propellers.

Table 1: Propeller particulars

Variables	P1	P2	P3
No. of blades	5	5	5
Diameter(m), D	2.20	2.15	2.20
P/D(mean)	0.76	0.78	0.76
EAR	0.90	0.88	0.90
Skew extent(degree)	25.0	15.0	8.7
Rake(degree)	3.0	3.0	3.0
Max. thickness/D at 0.6R	0.0222	0.0235	0.0261
Design J	0.453	0.438	0.438
Material	RHBsC1	RHBsC1	RA1Be3

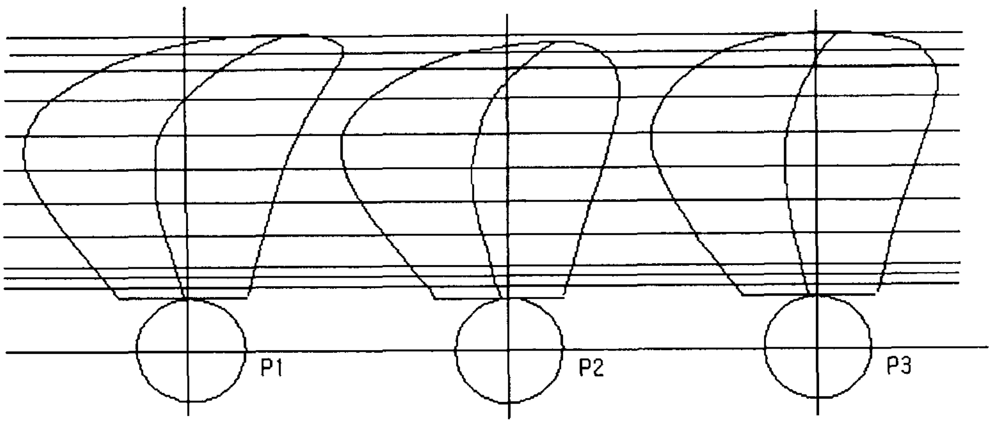

Figure 1: Outlines of propeller blades

3 Propulsion system design

The propulsion system for medium and high speed marine engine consists of the prime mover, the reduction gear, the clutch, the shaft and propeller, and the control units. The reduction gear is adopted to give the optimum propeller rotational speed from the high-speed prime mover. Especially for the present vessel the time duration for the reversal of the propeller rotation is essential, and hence the reversible reduction gear with the frictional clutch was selected. The control unit links the prime mover, the shaft and the propeller, and is designed to control the engine governor, the clutch, the shaft breaker and the propeller pneumatically.

Table 2: Sea trial records

No.	Trial Items	Prop. ID	Control	Trial Results	Prop. Cond.
T1	Speed trial	P1	OCS	Speed acceptable; Low vibration	
T2	Crash astern; Crash ahead	-ditto-	-ditto-	Red. Gear damaged, Both Engine RPM differed	Blade tip bent downstream
T3	-ditto-	-ditto-	-ditto-	Right Engine overload, Red. Gear damaged.	Blade tip bent Crack found
T4	-ditto-	-ditto-	MTC	Right Engine overload	Prop. replaced Blade tip bent
T5	-ditto-	-ditto-	MTRC	Right Engine overload	Prop. damaged
T6	Speed trial; Crash astern; Crash ahead	P2	-ditto-	Engine overload on Crash astern test; Red. Gear troubles	Prop. bent slightly
T7	-ditto-	-ditto-	OCS	Vibration level increase	-ditto-
T8	Speed trial; Turning Circle; Crash astern; Crash ahead	P3	GCS	More vibration than P1; Final acceptance trial	Prop. intact

4 Sea Trials

At the first speed trial, T1, the design speed was successfully achieved and the vibration level of the vessel was satisfactory. But at the second trial, T2, the reduction gear could not endure the crash astern maneuver, and the engines of both sides showed the different rotational speed, indicating the failure of propeller blades. From this point, various trials were carried out to locate the sources of the troubles and to resolve the problems. Table 2 shows the trial records, which will be described in detail in the subsequent sections. Four operational modes of the propulsion control systems were selected, varying the timing of the throttle valve and the maximum rotational speed of the shaft in crash astern and crash ahead maneuvers. Following abbreviations are used to illustrate the propulsion control modes:

- OCS(Original Control System): Automatic(Preset) throttle timing; Changes the rotational direction from max ahead to max astern direction instantly, vice versa.

- MTC(Modified Time Control): Throttle timing adjusted step-by-step manually.
- MTRC(Modified Time and RPM Control): MTC function and reduction of max astern RPM to 70% of forward max RPM.
- GCS(Gradual Control System): OCS function with gradual change of rotational direction.

5 Damage Description

The damaged status of P1 at T2 trial was very difficult to observe underwater due to the fouling of the blade surface, but all blades are found bent downstream as shown in Figure 2. Each blade has an almost straight bending line. In general, at almost all trials, the port propeller was either clean or less damaged than the starboard propeller. At T3, all propeller blades were found damaged(tip bending downstream and cracks) at or near 0.75~0.80% radius as added in Figure 2. It is at this point that the control system is reviewed and the need to check the throttle timing and to reduce the max astern power is raised. At T4, the throttle timing was adjusted manually, with the spare propellers replacing the damaged old ones. The starboard propeller blades however were found bent downstream near 80~90% radius, while only two blades of the port propeller were bent slightly downstream.

At T5, where the max astern power was reduced 50% in addition to the condition of T4, the crash astern trial led to the failure of the blade again, but the extent of the bending deformation was reduced from T2. The propeller was then redesigned with much more reduction of the skew extent with increased thickness near the blade tip trailing edge, which resolved the blade damage problem.

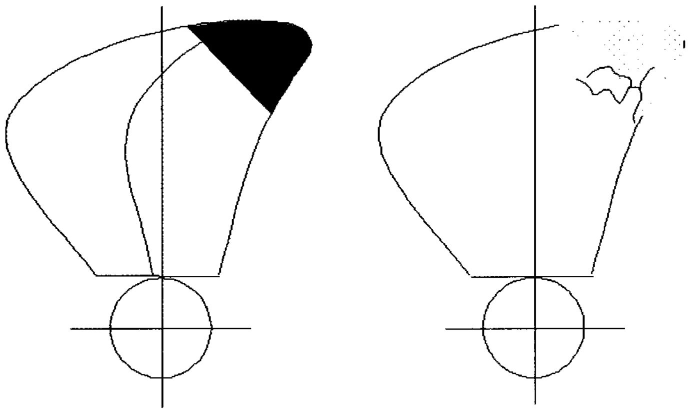

Figure 2: Typical blade damage in trials, T2(left) and T3(right)

6 Sea trial analysis

Since the propeller blades were damaged from the crash astern/ahead tests, we will focus our analysis only onto the failure-related tests. During the crash astern maneuver, the propeller blades

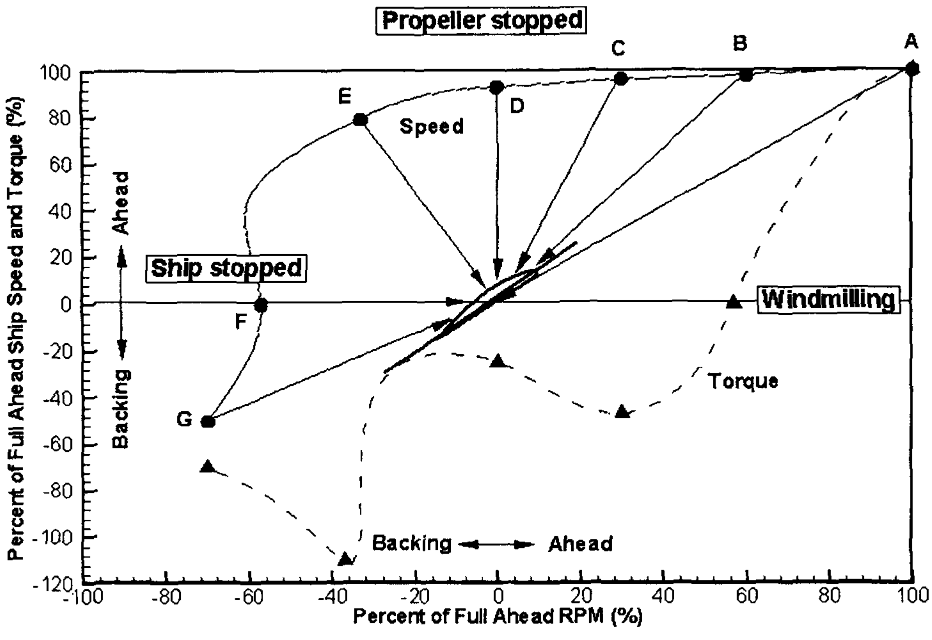

Figure 3: Inflow angle and torque variations during crash astern maneuver

experience the drastic change of inflow angle of attack, and at the same time the loading on the blades, as shown in Figure 3.

The non-uniformity of the inflow ship wake would add unsteadiness to the angle of attack and the loading. Figure 4 shows the RPM and speed versus the time during the crash astern maneuver for several trials. Remember first that the rotational direction of the engine is unchanged during operation. The reversible gear forcefully changes the direction of the propeller rotation instantaneously, usually within a few seconds. This is considered causing the amplification of the impact forces to the blades, leading to the failure of the blades. The modification of the throttle timing(T4) or the reduction of max astern power(T5) could not completely resolve the blade damage. Comparison with the parent ships was then made, as is added in Figure 4. It is clearly observed that the time duration for the crash astern of the parent ships is 2~4 times of the present vessel. This had increased the impact load by the same factors. In addition, the blade outline with 25 degrees skew drew attentions, since the blade bending occurred in the skewed tip region. The propeller was then redesigned, designated P2, with reduced diameter and skew angle and, of course, with the increased thickness where the bending occurred, then undergone a series tests at T6. Conference(1987).

The propeller P2 passed all the tests in T6, except the propeller blades were found slightly bent downstream. The reduction gear also suffered a slight trouble. The propeller P2 was also tested again under the contract control condition OCS at T7. With the reduction of the skew angle the vibration level went up, but was considered acceptable, because the vibration was relatively less crucial and insignificant at this stage. For the final acceptance, a third propeller P3 was designed and the sea trials were completed, but with gradual change of rotational direction.

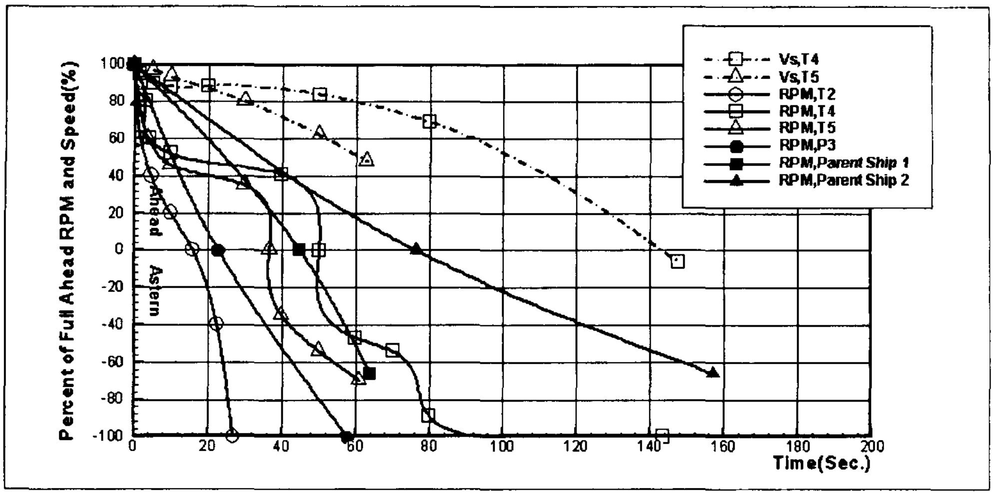

Figure 4: RPM and ship speed vs time for several crash astern tests

7 Propeller strength analysis

The propeller was designed by using the lifting surface code of Kim et al(1995) satisfying various Class rules as shown in Table 3.

Table 3: Thickness(T in mm) according to various Rules

	KR	DnV	LR	ABS	Design
T(0.25R)	90.6	87.6	98.0	97.8	98.0
T(0.60R)		36.4	41.6		48.8

The skew extent of P1 was 25 degrees, and hence there was no need for the detailed finite element calculation. The blade failure however led to the FEM calculation for P1 and all the subsequent propellers. The program proSTEC(propeller Stress Evaluation Code), developed by Nho et al(1989) and by Lee and Hong(1993), employs 20 node iso-parametric element, as shown in Figure 5, represents accurately the 3-dimensional curved surfaces and skewed geometry, and hence enables the prediction of the stress and deformation. The code was validated through the

Table 4: Max combined stress and max displacement(δ) in steady ahead condition for three propellers

Propeller	P1	P2	P3
$\sigma_{max}(kgf/mm^2)$	3.5	2.9	3.3
$\delta(mm)$	4.5	1.4	1.4
$\sigma_{allowable}(kgf/mm^2)$	44	44	60
S.F.	13	15	18

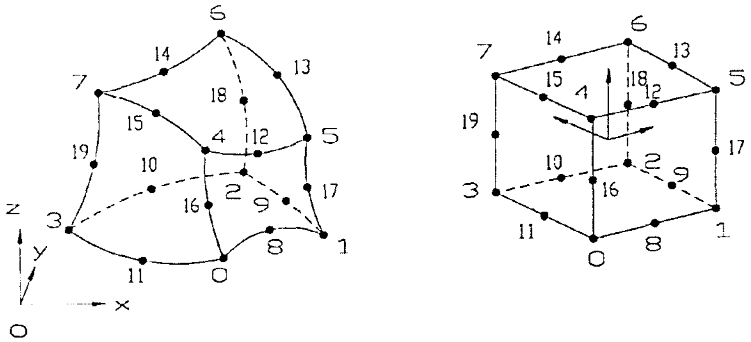

Figure 5: Coordinate system of HEXS20 element

comparative study with the experiments and other codes at the 18th International Towing Tank

At first, the max combined stress, σ_{max}(in kgf/mm^2), were compared with the allowable stress of blade material, $\sigma_{allowable}$, to get the safety factors for three propellers in steady ahead condition at the design speed, and summarized in Table 4. It is clearly seen that the safety factors are all far larger than the usual safety factor(S.F.) of 8. This implies all the propellers are safe in the traditional sense by the standardized judgment for the ordinary vessels with less severe crash astern performance and less amounts of propeller skew extents.

Since the blade failure occurred in crash astern maneuver, it was needed to get the unsteady hydrodynamic loading under the same condition, which was not yet obtainable. The blade toque reaches the maximum when the inflow velocity is at the second quadrant in Figure 3, when large separated flow around the sharp trailing edge is expected. According to Yamasaki et al(1983), the maximum stress level at the bollard backing condition is similar in magnitude to the maximum stress at the steady backward running condition. It was decided to compute the hydro-dynamic pressure distribution around the propeller blade at the bollard backing condition by using the lifting surface code of Kerwin and Lee(1976). The flow at the sharp trailing edge(or it should be called the leading edge in hydrodynamic sense) is surely separating or cavitating, but is assumed attached since the loading distribution is considered not so much different from that of the real flow. Figures 6 and 7 show the typical FEM meshes used and the typical stress contours for P1,

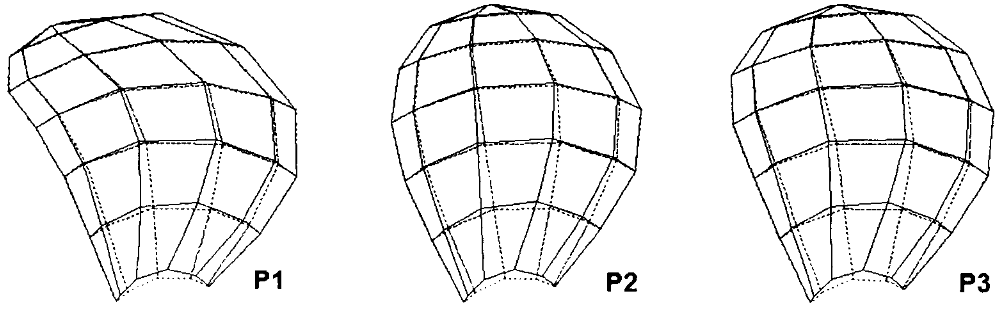

Figure 6: Typical FEM meshes used

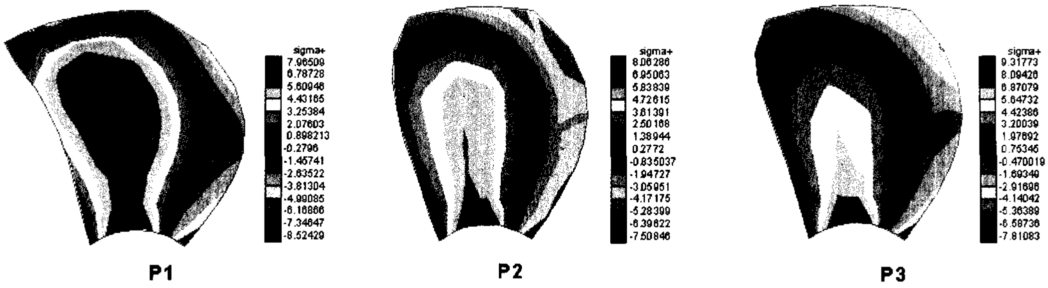

Figure 7: Typical stress contours for P1, P2 and P3 in bollard backing condition

P2 and P3, respectively. Note that the location of the max stress for P1 coincides with the location of the blade failure.

It may be observed from Figure 7 that the maximum tensile stress appears at the suction side of the blade very close to the trailing edge near the tip, where the tip bending and the crack were found after the crash astern tests. Similar results had been reported by Yamasaki et al(1983), Luttmer et al(1984) and Sunnersjo(1984). Table 5 summarizes the FEM analysis results together with the safety factors.

It should be noted first in bollard backing condition that the safety factor for P1(which failed in crash astern maneuver) is only 5.1, that for P2(which suffered a slight bending) 14.7 and that for P3(who was intact) is 19.4. Although the number of data is not sufficient to derive any criterion, it is clear that the safety factor computed at the bollard backing condition should be around 18$\sim$20. This value may be applicable with caution to the vessel with specific equipments such as the reversible reduction gear and the control system similar to the one installed to the present vessel. The flow in crash astern is surely unsteady, highly turbulent and separated, and hence the criterion above may only be used until the finite element analysis in the time domain is carried out with the unsteady hydrodynamic loading around the propeller at the same condition.

Since the stress level is proportional to the square of the rotational speed, the safety factor may be doubled by reducing the max astern rotational speed down to 70% of the forward maximum rotational speed. This may be applicable only when the time for the change of the rotational direction of the shaft is elongated from the present propulsion control system.

Table 5: Max combined stress and max displacement(δ) in bollard backing condition for three propellers

Propeller	P1	P2	P3
Damaged?	Yes	No	No
$\sigma_{max}(kgf/mm^2)$	8.6	3.0	3.1
$\delta(mm)$	3.5	1.3	1.0
$\sigma_{allowable}(kgf/mm^2)$	44	44	60
S.F.	6.1	14.7	19.4

8 Concluding remarks

A series of detailed study was performed to identify the sources of the propeller blade failure and resolve the problem systematically, by use of the theoretical tools and by the direct measurement in the full-scale sea trials.

The present vessel has a different propulsion control system from the parent ship, which caused the failure of the reversible reduction gear and the propeller blades during the crash astern maneuver. Instantaneous change of rotational direction of the propeller amplified the dynamic effect of the impulse, which induced severe loads both to the reduction gear and to the propeller.

Rule requirements of various Classification Societies for the propeller blade thickness are found not sufficient for the propeller with 25 degrees skew and the unusual reversible gear control system.

Quasi-steady analysis for propeller blade strength using FEM code in bollard backing condition indicates that the safety factor should be order of 18~20 to avoid the structural failure for the selected propeller geometry and reduction gear system.

For vessels requiring unusual ability in crash astern maneuver, the structural behavior of the propeller blades should be carefully evaluated and the thickness near the tip trailing edge should be reinforced.

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