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Simulation of Bent Trailing Edge of Propellers by Shot Blasting

Takao Sasajima*, *Member*

Summary

Bent trailing edge of propeller blades was studied in view of plastic deformation caused by cumulative impact load due to collapse of cavity.

It is found that the geometrical shape and microstructure of bent trailing edge of propeller blades are similar to those by shot blasting. These facts not only throw light on the mechanism of bent trailing edge but also lead to a simulation method.

This simulation method will be used for studying the intensity of load due to collapse of cavity quantitatively and for developing an effective prediction method of both bent trailing edge and cavitation erosion of propellers.

1 Introduction

Bent trailing edge is a bend of trailing edge of propeller blades towards pressure side. The phenomenon can be simulated in cavitation tunnel on model propellers and it is generally recognized that this is caused by so called "cloud cavitation" which occurs when a propeller operates in non-uniform wake of a ship.¹⁾

Bent trailing edge leads to change of effective pitch of a propeller, thus causing torque-rich and on the other hand stimulates cavitation erosion on the blade as a result of change in cavitation characteristics. How to prevent bent trailing edge?

The problem is approached from the two ways, the one refinement of propeller design from hydrodynamic view point and the other development of erosion resisting material. Hydrodynamic aspect can be simulated in cavitation tunnel, but no method is available to extend the model results to full scale. In developing a new material, nature of the exerted force on the blades by the collapse of cavity must be known. It is essential therefore to look for a method to evaluate quantitatively the intensity and nature of the load due to collapse of cavity.

Few works have been published since van Manen²⁾ tried to explain the cause of bent trailing edge in connection with cloud cavitation. Theoretical attack of the problem was made by van Wijngaarden³⁾, who calculated the mean pressure of the collective collapse of gas bubbles and suggested a possible cause of bent trailing edge. Cloud cavitation and resulting cavitation damage, however, is so complex that present knowledge is far from the quantitative evaluation of the intensity of cloud cavitation.⁴⁾

In the present study, an attempt has been made, therefore, to simulate bent trailing edge of propeller blades by means of mechanical external force, quantity of which can be evaluated easily. Several methods have been tried, and finally shot blasting was found out to be suitable for the simulation of bent trailing edge. The simulation was examined not only from view point of geometrical shape of bend but also metallographical structure.

* Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd.

2 Bent Trailing Edge of Ship Propellers and Reproduction by Model Tests

In order to grasp the nature of bent trailing edge of propellers, the shape and the amount of bent trailing edge of ship propellers were observed when the ships were docked. Further bent trailing edge was reproduced by model tests in cavitation tunnel to examine it more in detail.

2.1 Bent Trailing Edge of Ship Propellers

Fig. 1 shows an example of bent trailing edge observed on the propeller of a cargo liner, made of high tensile brass. According to the survey of the inspection record of propellers almost all the propellers made of high tensile brass suffer from a certain extent of bent trailing edge, even though cavitation erosion on back side was not so severe.

Fig. 2 shows another example of bent trailing edge measured on the propeller of 120,000^{DWT} tanker, which is made of nickel aluminium bronze (NiAlBz). Extent of bent trailing edge is limited to a small range which corresponds to the area of cloud cavitation.

Fig. 3 shows an example of bent shape measured on another ship, 56,000^{DWT} ore and oil carrier. The bent shape is characterized by gradual change of curvature without sharp corner.

2.2 Reproduction of Bent Trailing Edge on Model Propellers

Bent trailing edge was reproduced on model propellers made of corrosion resisting aluminium by cavitation tests in non-uniform wake. Fig. 4 shows the test results on model propeller A, with pit holes distributed on the back side. Cloud cavitation which caused these bent trailing edges was also shown in Fig. 5. The bent shape was measured precisely by use of the point drilling machine after proper test intervals. The results are shown in Fig. 6. The bent shape of a model propeller quite resembles that of ship propellers as the curvature of the bent part changes gradually. Further Fig. 7 shows extension of bent trailing edge with cavitation test time. The amount of bend increases rapidly soon after the beginning of cavitation test but gradually it tends to be saturated. The extension of bent part in radial and chordwise direction is small, which means the bend extends mainly in its amount.

Another point, which was revealed through these model tests, was that the reproduction of bent trailing edge on model propellers, made of the same material as ship propellers, i.e. high tensile brass

Ship; 12,000^{DWT} Cargo Liner
Propeller; High tensile brass $D=5.6\text{m}$
Inspection; About 5 years after completion

Fig. 1 Bent Trailing Edge Observed on a Full Scale Propeller (Ship Prop. a)

Fig. 2 Extension of Bent Trailing Edge of a Full Scale Propeller (Ship Prop. b)

Fig. 3 Example of Bent Shape Measured on a Full Scale Propeller (Ship Prop. c)

Fig. 4 Bent Trailing Edge Reproduced on a Model Propeller (Model Prop. A)

Fig. 5 Cloud Cavitation Which Caused Bent Trailing Edge (Model Prop. A)

Fig. 6 Example of Bent Shape Measured on a Model Propeller (Model Prop. A)

Fig. 7 Extension of Bent Trailing Edge with Test Time (Model Prop. A)

or nickel aluminum bronze, was almost impossible. This fact implies not only that intensity of cloud cavitation reproducible in cavitation tunnel is not high enough compared with strength of material and such is the limitation of usual cavitation tunnel for studying this problem. Thus, in order to examine the effects of propeller material or blade section shape on bent trailing edge and to establish

the correlation between model propellers and ship propellers, attempts were made to find out a method of simulation of bent trailing edge, which can be applied to any materials.

2.3 Properties of Bent Trailing Edge

Effectiveness of the simulation must be examined not only through the bent shape but also other additional properties which characterize the phenomenon. Thus from the above mentioned observation of bent trailing edge of ship propellers and examination of reproduced bent trailing edge of model propellers, the features of bent trailing edge are summarized as follows;

- (1) Locallity (deformation occurs where the cavity collapses)
- (2) Gradually changing curvature with changing the local thickness of a blade section
- (3) Rapid increase of bend in early stage and tendency of saturation in later stage.

3 Simulation of Bent Trailing Edge of Propellers by External Force

Considering the characteristics of the bent shape, following tests were conducted;

- (1) Low-cycle, high-load fatigue test (2cpm)
- (2) High-cycle, high-load fatigue test (1240cpm)
- (3) Impact fatigue test

(1) and (2) were intended to check whether bent trailing edge of propellers can be simulated by the sinusoidally changing concentrated load. Test pieces were made of the same material as model propellers, supported as cantilevers and loaded near the free end. Fig. 8 shows an example of the test results. The bent part was limited to the zone close to the load and cracks were found near the supporting edge (In this figure, the deformation due to cracks, which is propotional to the distance from the supporting edge, is eliminated). Almost the same results were obtained in case of high-cycle fatigue tests.

(3) was intended to check the effect of shock wave caused by impact load on local deformation. The results are not shown here, but the test pieces did not bend when the load is low and only the bend due to cracks near the supporting edge was observed when the load was high. Of course, dents and cracks were found at the loading points.

From these test results, it was concluded that the concentrated and cyclically changing load is not suitable to reproduce the same bend as that of propeller. In other words, bent trailing edge is not a kind of fatigue deformation. Thus the properties of the load due to collapse of cavity are examined. Table 1 shows the classification of the property of the load due to cavitation deduced from the observation of cloud cavitation. The most distinct features of the load seem to be highly frequent, cumulative, dispersed, and impact, imagined from the pit holes distributed on the back side of bent trailing edge as shown in Fig. 4. One of the hints to get such kind of mechanical force is that the erosion due to water or liquid drops is quite similar to that due to cavitation⁵⁾. Further, according to Engel^{6,7)}, collision of metal balls to metal target shows the same tendency of the collision of liquid drops to the metal target. So the shot blasting tests were planned to simulate the bent shape because it is easier to estimate the force or the loading conditions.

Fig. 9 shows the shot blasting method. Test pieces were set as cantilevers in the blasting room. The test piece section consists of 20% of the chord length from the trailing edge at 0.9R blade section

Fig. 8 Bent Shape of the Test Piece by Low-cycle Fatigue Test

Table 1 Conceivable Properties of Load due to Collapse of Cavity

Comments	Loading speed	Loading type	Loading position		Loading intensity
Most reasonable combination	High-cycle (High-frequency)	Cumulative	Distributed	Dispersed	High (Larger than yield stress)
		Impact		Continuous	
	Low-cycle (Low-frequency)	Continuous (for example, Sinsoidal)	Con- centrated	Point Line	Low (Lower than yield stress)

of the model propeller A and to fit the size of the shot and the shot blaster, the length of the test pieces was magnified 10 times that of the model propeller.

Fig. 10 shows the measured bent shape of the test piece in comparison with that of cavitation tests. Deformed part is still limited to the free-end side in case of shot blasting, but curvature distribution along the bent part resembles the bent trailing edge. Further, the bent shape is non-dimensionalized and compared with that of the model propeller as shown in Fig. 11, which is very encouraging for simulation method.

Another correspondence of shot blasting method is that the extension of bend with time as shown in Fig. 12 shows the same tendency as that of model propeller, as already shown in Fig. 7.

Thus it can be concluded that bent trailing edge of propellers can be simulated by shot blasting method, which is thought to match the load due to collapse of cavity. But in order to ensure this method, further examination of the microstructure of the bent part was carried out.

Fig. 9 Shot Blasting Test Method

Fig. 10 Comparison of Bent Shape of Shot Blasted Test Piece with That of Model Propeller

Fig. 11 Comparison of Non-dimensionalized Bent Shape

Fig. 12 Extension of Bent of the Shot Blasted Test Piece with Blasting Time (Corrosion resisting aluminium)

4 Metallographical Examination of Bent Part

4.1 Microstructure of Shot Blasted Part

At first, microstructure of shot blasted test pieces was examined. Fig. 13 (1) shows a test piece of corrosion resisting aluminium after shot blasted. Metal flow is observed clearly over the whole surface of the shot blasted area from this photograph. Fig. 13 (2) shows microstructure of the center plane section of the test piece. Crystal grains in the shot blasted surface were destructed by intensive load. Under that layer flatly deformed crystal grains were seen and the depth of the layer is about 5 to 10% of the whole thickness. Hardness of the deformed layer is very high as follows;

Fig. 13 (2) Metallographical Examination on the Bent Part of Shot Blasted Test Piece (Corrosion resisting aluminium)

- ① 140—110 H_v
- ② 83—95 H_v (H_v ; Micro Vickers Hardness, Load 50 g)
- ③ 93 H_v

(Positions of ①, ②, ③ are marked in Fig. 13(2))

These data show the existence of the work-hardened thin layer under the shot blasted surface.

Shot blasted test pieces made of the same material as ship propellers, i.e. nickel aluminium bronze, were also examined. Shot blasting conditions are quite the same as those of corrosion resisting aluminium. Metal flow is also observed over the blasted surface as shown in Fig. 14, but it is not so severe as that of corrosion resisting aluminium. Microstructure under the shot blasted surface shows that crystal grains of α -phase become flat and grain boundaries become not to cross the blasted surface, as shown in Fig. 14. Hardness of the shot blasted surface is about 60 to 70% higher than that of unblasted part, but the depth of the work-hardened layer is rather thin and about 10% of the whole thickness as shown in Fig. 15.

Shot Blasted Surface Unblasted Surface
Fig. 14 Metallographical Examination of the Bent Part of Shot Blasted Test Piece (Nickel aluminium bronze)

Fig. 15 Hardness Distribution across Bent Part of Shot Blasted Test Piece (Nickel aluminium bronze)

These results show the bend of shot blasted test pieces is caused by the plastic elongation of the thin surface layer of the shot blasted side. This mechanism is quite the same as the bend of the Alumen gauge⁹⁾, though the test pieces in the simulation test were hold as cantilevers.

4.2 Microstructure of Bent Part of Propellers

Metallographical study of the bent part of full scale propellers was limited to the propellers from which the samples could be cut off. Fortunately, we had the chance to take samples from the propeller of 90,000^{DWT} tanker. The bent shape is shown in Fig. 16. In order to check the degree of plastic deformation, the test piece was heated to the recrystallization temperature. Microstructure in Fig. 16 shows the thin surface layer with slip bands under the eroded surface, which means severe

Ship; 90,000^{DWT} Tanker
Propeller; High tensile brass
 $D=7.2$ m
Inspection; 4 Years after
Completion

Back Surface (B—Side) Microstructure of Bent Part (x100) Face Surface (F—Side)

Fig. 16 Metallographical Examination on Bent Trailing Edge of a Full Scale Propeller (Ship Prop. d)

plastic deformation. The depth of the surface layer is about one tenth of the blade thickness at the radius.

The hardness of the eroded surface of the bent part increased about 20% of the original material, as shown in Fig. 17. The thickness of the work-hardened layer is almost the same as that estimated from slip bands, but deformation of crystal grains are not yet recognized.

In the same way, examination of microstructure of the bent part on model propellers was tried. Fig. 18 shows the bent shape of the No. 1 and No. 3 blade of the model propeller B and microstructure of them. As the outer radius of the propeller blades were made of corrosion resisting aluminium plates, the fiber structure due to cold rolling remained and the deformation of crystal grains are not clear. But judging from the black or dark tone near the eroded surface, shown in the photograph of microstructure, it is estimated that the thin surface layer suffers from severe plastic deformation, because the black or dark tone near the eroded surface is the result of the etching proceeded selectively in activated area. Hardness increased in the surface layer ③ as follows;

Fig. 17 Hardness Distribution across Bent Trailing Edge of a Full Scale Propeller (Ship Prop. d)

No. 1 Blade (0.8 R) $\times 2$

No. 3 Blade (0.85 R) $\times 2$

No. 1 Blade

No. 3 Blade

Microstructure $\times 100$

Fig. 18 Metallographical Examination on Bent Trailing Edge of a Model Propeller (Model Prop. B)

- ① 94—89 H_v
- ② 78—85 H_v (H_v ; Micro Vickers Hardness, Load 50 g)
- ③ 79—86 H_v

(Position of ①, ②, ③ are marked in Fig. 18.)

Summarizing these metallographical examination of the bent part caused by cavitation, the following two points are picked out;

- (1) Under the eroded surface of the bent part, deformed and work-hardened thin layer is formed and its depth is lower than 20% of the whole thickness.
- (2) Under the eroded surface of the bent part, metal flow (deformation of crystal grains) or slip bands are observed.

These are the same results as metallographical examination of the bent part caused by shot blasting.

Thus it is concluded that the mechanism of bent trailing edge of propeller blades is similar to the bend due to shot blasting, as explained schematically in Fig. 19 and these results strongly support the simulation method.

Another effective examination which will give the evidence to this simulation method is residual stress distribution across the bent part of the blade section, but it is not reported here because of lack of proper measuring technique. Recent development in X-Ray analysis in this field gives us the chance to check it, and the results of the examination will be given in the near future.

5 Concluding Remarks

In order to establish the effective method to prevent bent trailing edge of propellers, a simulation technique of bent trailing edge was found out. Through the examination of the simulation method, light was thrown on the mechanism of bent trailing edge by the analogy of the bend by shot blasting. This interpretation, i.e. bent trailing edge is caused by the plastic elongation of thin surface layer under the eroded surface by cumulative, dispersed, impact load due to collapse of cavity, can be accepted as reasonable, when we see the phase of metal flow by cavitation shown in Fig. 20 (Model Prop. A).

Fig. 19 Mechanism of Bent Trailing Edge

Fig. 20 Plastic Deformation on the Bent Part due to Collapse of Cavity

It is already known that the amount of bend changes with shot size, collision speed of shots, blasting time, and mechanical properties of material. The first two items are concerned with the impact force or pressure which correspond to the strength of the shock wave emitted when spherical cavitation bubbles collapse, or to the impact pressure due to collision of the microjets when hemispherical cavitation bubbles collapse. Thus this simulation method will give quantitatively effective approach to prevent bent trailing edge of propellers and to study cavitation erosion problems.

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References

- 1) J.D. van Manen: Fundamentals of Ship Resistance and Propulsion, Part B, Propulsion, International Shipbuilding Progress.
 - 2) J.D. van Manen: Bent Trailing Edges of Propeller Blades of High Powered Single Screw Ships, Proceedings IAHR—Symposium, Sendai, (1962), p. 461.
 - 3) L. van Wijngaarden: On the Collective Collapse of a Large Number of Gas Bubbles in Water, Eleventh International Congress Applied Mechanics, (1964), p. 854.
 - 4) T. Sasajima: On Cavitation Erosion Test Method by Using a Painted Model Propeller, (in Japanese) The Shipbuilding Industries, Vol. 4, No. 4, (July, 1972).
 - 5) G. Hoff, G. Langbein and H. Rierger: Material Destruction due to Liquid Impacts, Erosion by Cavitation or Impigement, ASTM Technical Publication No. 408, (1966), p. 42.
 - 6) O.G. Engel: Pits in Metals by Collision with Liquid Drops and Rigid steel Spheres, Journal of Research of the National Bureau of Standards, Vol. 63A, No. 1, (Jan.—Feb., 1960), p. 61.
 - 7) O.G. Engel: Pits in Metals by Collision with Liquid Drops and Soft Metal Spheres, Journal of Research of the National Bureau of Standards, Vol. 62, No. 6, (June, 1959), p. 229.
 - 8) J.O. Alumen: Improving Fatigue Strength of Machine Parts, Mechanical Engineering, Vol. 65, No. 8, (1943).
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