Experimental Investigation on Capsizing and Sinking of a Cruising Yacht in Wind

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ABSTRACT

This paper describes the main finding of the investigation of the sinking accident of a 6.45 metre-long cruising yacht in September 2003 in Japan. Responding to the request from Japan's Marine Accident Inquiry Agency the authors executed a model experiment in beam wind for identifying the time-to-sink as well as stability calculations with and without water inside the yacht. The results indicate it could capsize when the wind velocity exceeds a threshold. Because of an opened hatch on the deck, water initially enters into the cabin. After capsizing, the water ingress process stops. However, if wind is strong enough to incline the capsized yacht, the yacht starts to return to upright condition but this transition stage provides an opportunity to further flooding. By systematically changing wind velocity in the experiment, the time to sink was recorded. In conclusion, the critical wind velocities for capsizing and sinking were estimated, and reasonably well explain the reason of this accident.

Keywords: *capsizing, time-to-sink, re-righting, sailing yacht, wind loading , flooded water*

1. INTRODUCTION

On 15 September 2003, a 6.45 metre-long cruising yacht capsized and then sunk in Lake Biwa, which is the largest lake in Japan, and seven of its twelve crew drowned. This yacht having a cabin and a fin keel has the stability range of more than 110 degrees and no significant waves existed in the period of the accident. Thus the reason why the yacht sank seemed to be puzzling. To identify the reason of this accident, the Marine Accident Inquiry Agency requested the first author to investigate this accident.

It is well established that a cruising yacht could capsize in heavy weather, often due to breaking waves. Several model experiments of capsizing and re-righting of cruising yachts have been reported. (e.g. Hirayama et al. 1994, 1995, Nimura et al. 1994, Deakin 2000) These were executed with breaking waves generated in model basins. In this accident, however, no significant waves existed on the lake. Thus, it was impossible for us to simply apply the established knowledge from the existing experiments.

Actual accident reports often indicate that capsize of sailing yacht does not directly result in sinking. This is because air can be trapped inside upside-down hull. Then there is a chance for the yacht to re-right with the attack of succeeding large waves. (Renilson et al., 2000) Why the capsizing of the yacht in the accident leaded to sinking was also an unsolved problem for us.

To provide possible solutions of these problems, we calculated restoring arm curves of the yacht and executed an experiment with a 1/5.7857 scaled model of the yacht, which had the cabin, mast, sail, keel and so on, in a towing tank with a blower. As a result, we realised the process from capsizing to sinking in model scale. By using these calculated and experimental results together with the witness reports, we presumed a possible scenario where the yacht capsizes and then sinks.

2. ACCIDENT

The yacht that sank was built as one of a class produced for pleasure cruising and/or racing in 1980's. It was rigged as sloop, and has a cabin, fin keel, rudder and an outboard motor. The hull was made of GRP. The cabin had two openings; a companionway and a hole for ventilator on deck at the bow. The position of this bow hole was slightly shifted to the port side and its area was 0.0064m^2. Here the ventilator itself was not equipped at the accident. The principal dimensions and body plan are shown in Table 1 and Figure 1, respectively. It was allowed to carry ten adults by the Administration. Here two children can be regarded as equivalent to one adult by law.

Table 1 Principal particulars of the yacht at the light ship condition.

Length over all	6.45 m
Maximum breadth	2.48 m
Maximum depth	1.17 m
Draught at midship	1.30 m
Ship displacement	1.045 ton
Initial trim angle by stern	2.1 degrees
Metacentric height	0.935 m
Area of main sail	12.56 m^2

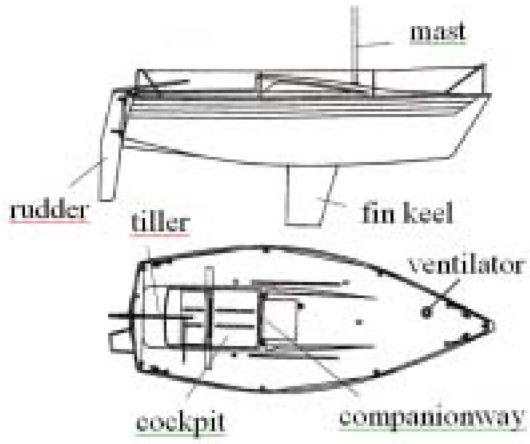

Figure 1 General arrangement of the yacht**.**

On 15 September 2003, the yacht departed from a harbour situated in the western shore in Lake Biwa by using the outboard motor at 16:30. Seven adults and five children were onboard. This means the number of crew can be below the maximum allowed one. The companionway and the bow hole were open. None of the crew except for two children wore life-vests.

At 16:33, the skipper stopped the motor and the yacht started to sail with a main sail only. Then the yacht sailed closed-hauled on port tack with a leeward heel of about 15 degrees and estimated speed of about 1.3 knot. Here the main sheet was fixed by using the cam cleat. Four adults and four children were on the port side, one adult in the centre and two adults and one child on the starboard side. All of them were on deck.

At 16:49, the skipper ordered to tack about and helmed up. Then the yacht was on starboard tack but the yawing motion continued beyond the expected close-hauled course on the new tack. At the same time the roll towards the new lee side violently increases. It was probably because the skipper failed to helm amidships and to release the main sheet from the cleat. Because of significant roll towards port side, one adult and one child situated on the starboard-side deck dropped onto the main sail and then all other crew dropped into the water and the yacht completely capsized.

Shortly after the yacht started to re-right but its stern was under water due to flooding. At 16:50, the yacht sunk from the stern.

It was a fine day. According to the measured data from a Shiga University's observation buoy situated with the distance of 4.5 km from the accident, the mean wind speed ranges from 7.4 m/s to 8.5 m/s and the maximum was from 11.5 m/s to 11.8 m/s. Because of the very limited fetch and duration, waves were very short. Three adults and two children survived but the others including the skipper were drowned or still missing.

3. HYDRO STATIC CALCULATION

Hydrostatic calculation was carried out for the yacht with and without flooded water inside the cabin. Weights and positions of the crew and equipment were estimated with available data from the Shiga Prefecture Police. Weight and trim of the light ship were obtained from the ship yard data.

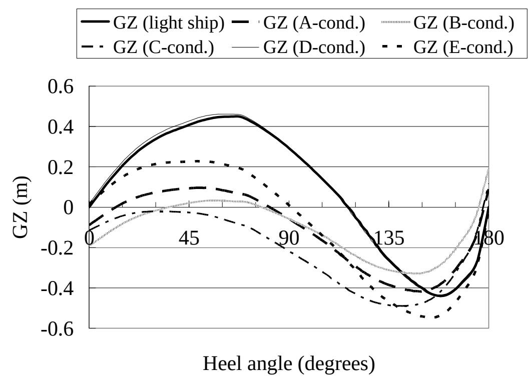

Figure 2 Restoring arm curves without flooded water.

As shown in Figure 2, in the light ship condition, the angle of vanishing stability is 116 degrees and the maximum restoring arm is 0.45 m. Recent research of the Japan Craft Inspection Organization (Takaishi, 2000) recommends the angle of vanishing stability to be 100 degrees or over. Thus, the yacht seems to have sufficient stability. This is because the weight of the ballast in the fin keel is about 31.6 % of the light ship displacement. In the loading condition at the accident (the condition A in the figure), however, the restoring arm is significantly reduced because of weight of the crew (593 kg) on the deck. The ship has a port-side heel of 12 degrees due to unsymmetrical loading, the angle of vanishing stability of 81 degrees and the maximum righting arm is 0.096 m. Since the IMO Intact stability code requires the maximum righting arm of 0.2 m, static stability in this loading condition can be regarded as insufficient. This is because the crew weight on deck corresponds to 60 % of the light ship displacement.

The condition B indicates the case all crew are shifted to lee side with 300 mm, which results in the initial heel of 36 degrees. The condition C is the case one adult and one child moved to the centre of main sail. Here restoring arm is always negative. The condition E will result in the case all other crew dropping into the water from the condition C. Here the static stability increases. The condition D also results in the case all the crew dropping into the water, which is almost identical to the light ship condition.

Because of opening of the cabin, a certain amount of flooded water could exist once capsizing occurs. Figure 3 indicates restoring arm curves with a certain amount of flooded water inside the cabin but here we ignore further water ingress and egress through the opening. Figure 4 shows change of trim angle due to heel.

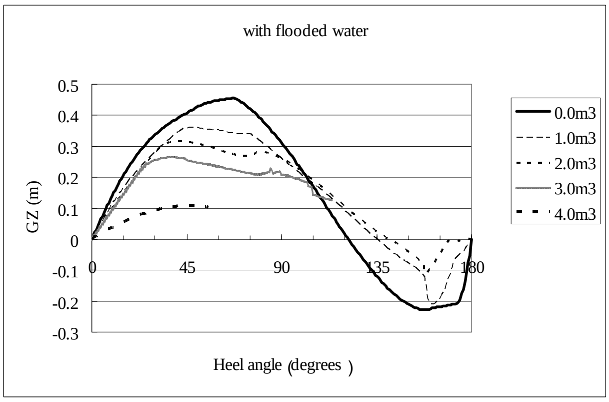

Figure 3 Restoring arm curves with flooded

water.

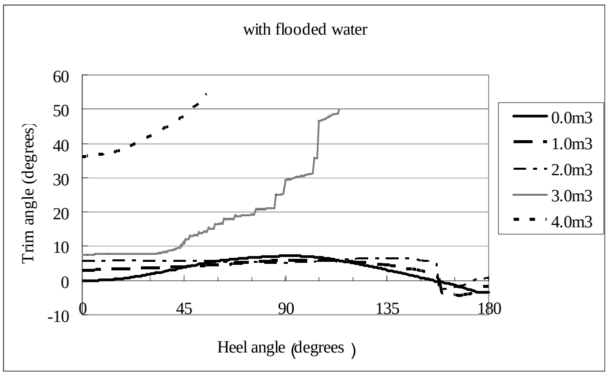

Figure 4 Trim angles with flooded water. Here the positive trim means the trim by the stern.

In case of the flooded water of 0 and 1 m^3, slopes of the righting arm at the capsized condition (180 degrees) are very steep. Thus, the capsized yacht is very stable. In case of $2m^3$, however, the slope becomes zero. This means the capsized yacht could start to re-right if flooding exceeds this amount of water. This fact was confirmed for a similar yacht by a full-scale experiment and calculation of Nomoto (2000). If water flooding progresses further, the trim by the stern increases with heel and the righting arm curves cannot be properly calculated.

4. MODEL EXPERIMENT

For investigating the dynamic process from capsizing to sinking, a model experiment was conducted at the towing tank of Osaka Prefecture University, which can realise wind on the water surface with a blower. The tank is 70 m in long, 3 m in wide and 1.5 m in deep.

The 1/5.7857 scaled model of the yacht was used in the experiment because the capsized model with the mast should not touch the bottom of the tank. As a result, the model length was 1.1 m. Because of flow separation due to the fin keel and sail, the scale effect due to viscosity can be regarded as negligibly small. And the scale effect of air compression is estimated as about 10 % or less in the draught of the capsized yacht. (Nomoto, 2000)

The model was equipped with a mast, a boom, a set of spreaders, a main sail, a main sheet, a main sheet traveller, a kicking strap, a main halyard, a fore stay, a back stay, an upper side stay, a lower side stay, a rudder, a tiller, a fin keel, an outboard motor and so on. The internal layout of the cabin including bulkheads and longitudinal frames and thickness of the hull were also geometrically scaled.

By adjusting the weight inside the fin keel, the vertical and longitudinal centres of gravity of the light ship were set to correspond to the full scale ship and were confirmed by an inclining test. The roll test in calm water indicated that the natural roll period at upright condition was 3.6 seconds in full scale and no periodic roll was observed at capsized condition because of large roll damping due to the sail.

If the skipper failed to helm amidships and to release the main sheet, the yacht suddenly suffered beam wind loading after the tacking about. Based on this assumption, the model was placed to beam wind conditions in the tank with a constant wind velocity. The model was initially held upright but at the start of the experiment the restraint was released. As a result, sudden beam wind loading was simulated.

In the experiment, the weight corresponding to one adult and one child was initially attached to the mast at the height of the centre of the main sail, and the weight was designed to mechanically leave the mast at the heel of 120 degrees. Once the restraint of the yacht model was suddenly removed, the model rolled significantly beyond the static equilibrium of heel and stopped at the equilibrium angle of energy.

The static equilibrium can be estimated with the comparison between wind heeling moment and restoring moment as shown in Figure 5. Here the wind heeling moment, M_W, is assumed to be calculated with the following formulae.

$$M_W = \tfrac{1}{2}\rho_A V^2 A_{S0} z_{s0} C_D \cos^2\phi + \tfrac{1}{2}\rho_A V^2 A_{H0} z_{H0} C_D \cos^2\phi + \tfrac{1}{2}\rho_A V^2 A_{H90} z_{H90} C_D \sin^2\phi \quad (1)$$

for $0 < \phi < \pi/2$

$$M_W = \tfrac{1}{2}\rho_A V^2 A_{H180} z_{H180} C_D \cos^2\phi + \tfrac{1}{2}\rho_A V^2 A_{H90} z_{H90} C_D \sin^2\phi \quad (2)$$

for $\pi/2 < \phi < \pi$

where ϕ: heel angle, ρ_A: air density, V: wind speed, C_D: drag coefficient, A_S: lateral projected area of sail, A_H: lateral projected area of hull, z_S: height of centre of lateral projected area of sail above the water from the centre of underwater hull, z_H: height of centre of lateral projected area of hull above water from the centre of underwater hull and sail. And the suffices such as "90" indicate the heel angle.

The value of C_D is assumed be 1.11, based on the IMO weather criterion (Japan, 2005). The restoring moment between 0 and 120 degrees in heel corresponds to that of the condition E and that beyond 120 degrees does to that of the condition D because of the loss of weight. As shown in Figure 5, static equilibria exist even in the case of the wind speed of 11 m/s.

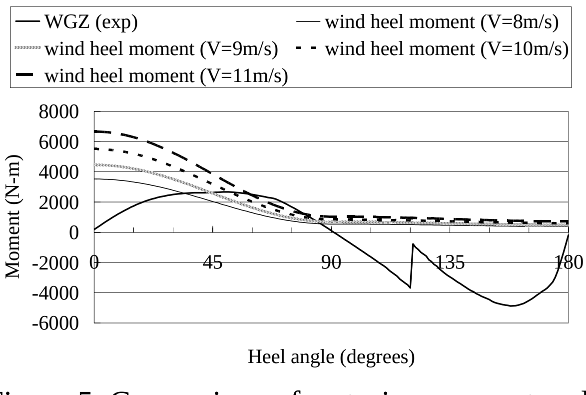

Figure 5 Comparison of restoring moment and wind heeling moment in case of model experiment.

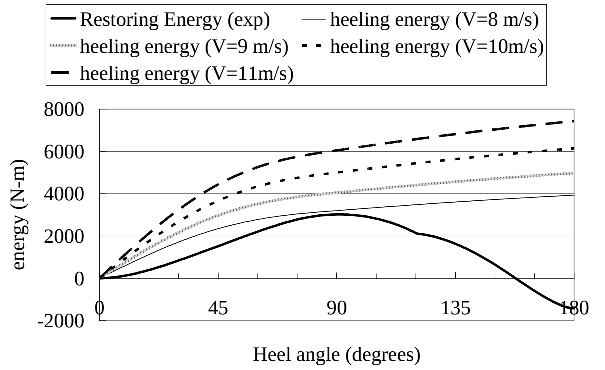

Figure 6 Comparison of restoring energy and wind heeling energy in case of model experiment.

As shown in Figure 6, the equilibrium of energy does not exist even with the wind speed of 8m/s, In the experiment, however, the yacht model capsized only with 10 m/s or over in wind speed. (See Figure 7.) It can be presumed that energy dispassion due to roll damping up to 90 degrees is about 1kN-m.

Once capsizing occurs, the roll motion immediately stops because of large roll damping due to the main sail around the capsized condition. However, the static heel angle here is not 180 degrees because of wind heeling moment acting on the fin keel and capsized canoe body as shown in Figure 8. If this additional heel angle from 180 degrees is large enough, part of companionway and (/or) the ventilator hole can emerge and then water ingress and air egress can start. As indicated in the restoring arm curves with flooded water inside the hull, if flooded water amount exceeds 2 m3, capsized condition of the model becomes unstable and then the model starts to re-right.

If the model starts to re-right, the trim by the stern also increases. This agrees with the results of righting arm calculation with flooded water. When the roll angle reaches about 270 degrees, the stern including companionway completely submerges. Thus, if the ventilator hole on the bow deck is closed, air inside the cabin is trapped and therefore the model cannot sink. In contrast, if the ventilator hole is open, air inside the cabin gradually escaped through the hole and finally the model sinks as shown in Figure 9.

Figure 7 Photo of the yacht model just before capsizing under the wind velocity of 11 m/s.

Figure 8 Photo of the capsized yacht model under the wind velocity of 11 m/s.

Figure 9 Photo of the sinking yacht with the full-sized bow hole under the wind velocity of 11 m/s.

Table 2 Summary of model experiment. Here O: fully open, o: 20% open, X: closed, b: bow hole and ch: companionway.

wind speed (m/s)	b	ch	b	ch	b	ch	b	ch
	O	O	X	O	O	X	o	O
8	non-capsize							
9	non-capsize						non-capsize	
10	sink						sink	
11	sink		capsize		capsize		sink	
12	sink		capsize					
13.8			re-right					
14.5	sink		re-right		capsize		sink	
18	sink				fully re-right			

The experiment was carried out for several combinations of open or close bow hole and companionway as well as different wind velocities. The results are summarised in Table 2 and the time to sink from upside down is plotted in Figure 10. The threshold for capsizing exists between 9 and 10 m/s. If either the bow hole or the companionway is closed, the yacht model did not sink. This is because air flow requires both the bow hole and the companionway are open. In particular, in the cases the companionway is closed and wind speed is strong enough, the yacht model completely re-rights and sails again. However, these cases require stronger wind than the cases of sink because flooding from capsized condition with small opening is more difficult. With the same reason, when the wind speed increases time-to-sink decreases. If the bow hole is smaller, time-to-sink can be longer because of reduction of air flow speed but sinking cannot be prevented in the long run.

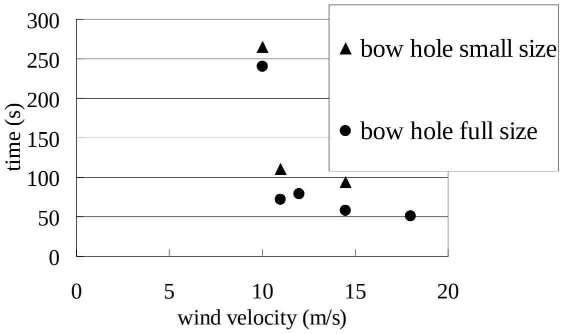

Figure 10 Time to sink of the yacht model from upside down in full scale. Here the companionway was open.

5. SCENARIO OF ACCIDENT

Based on the above investigation and witness reports, the authors presume the following scenario of the accident.

When the tacking about was executed, the skipper failed to helm amidships and to release the main sheet. Then the yacht drastically rolled toward leeward side. Because of roll, the crew on deck were moved to leeward and then one adult and one child dropped into the main sail. Subsequently all others dropped into the water. Under this condition the static equilibrium existed as shown in Figure 11, but the dynamic equilibrium did not exist, as shown in Figure 12, even with energy dispassion due to roll damping taken into account. Then the roll angle exceeds the angle of vanishing stability and therefore capsizing cannot be avoided.

This scenario could work even with the wind speed of 8 m/s. The measured data near the place of accident shows that the mean wind speed at the accident was about 8 m/s as described before. In addition, the authors also investigated the effect of replacement of crew positions at the tacking and confirmed that this is not the primary cause of the accident. The details will be published separately.

Once capsized, air inside the cabin was

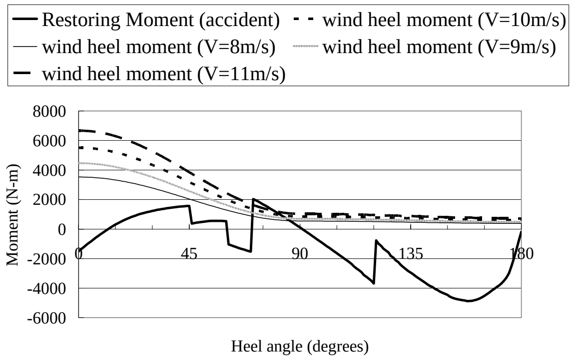

Figure 11 Comparison of restoring moment and wind heeling moment in case of accident.

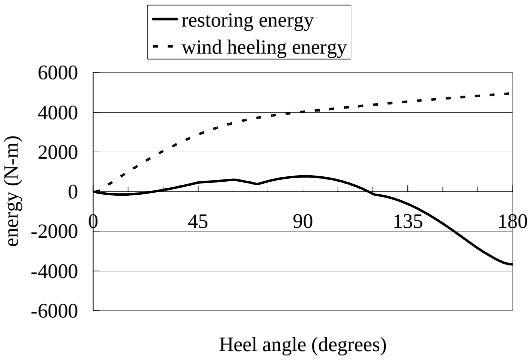

Figure 12 Comparison of restoring energy and wind heeling energy with 8m/s of wind speed.

completely trapped. However, the wind moment acting on the fin keel and canoe bodycould further incline the yacht from the fully capsized condition and the bow hole and part of the companionway could emerge. Then air can escape and water can enter into the cabin gradually. When the flooded water inside the cabin exceeds 2 m^3, the capsized yacht becomes unstable and the yacht starts to re-right. Further flooding during this transient process induces large trim by the stern. When the yacht almost re-rights, the companionway is completely submerged due to this trim by the stern. If the bow hole is closed here, air inside the cabin can be trapped and the yacht can be safe. Unfortunately, the bow hole was open. As a result, air inside the cabin escaped through the bow hole, and therefore the yacht sunk. The critical wind speed of this scenario is 10m/s while the measured maximum wind speed was about 11 m/s. This means the yacht could sink if she suffered a gusty wind at that time.

After the accident, several countermeasures were proposed. Shiga Prefecture enforced a new local rule for mandating the use of life vests for people on all powered pleasure boats in 2004. The Japan Sailing Federation (2004) warned that a small cruising yacht could capsize due to uncontrolled tacking or jibing. And Masuyama (2004) proposed to add small but sufficient buoyancy-aid inside the cabin of a small cruising yacht for preventing its sinking.

6. ANOTHER ACCIDENT

A sister yacht with the exactly same design also capsized on 28 October 2001 in Osaka Bay without the loss of human life. In this case the yacht capsized and then completely re-righted without sinking. The difference between the two yachts is discussed here.

The yacht at the accident in Osaka Bay had six adults and six children as her crew and all of them were on deck. Thus, the righting arm of this yacht could be drastically reduced like the yacht in Lake Biwa. The companionway and the ventilator at the bow were open.

The mean wind speed was about 8 m/s with some gust and the wave height was about 0.5 m. The yacht ran with its outboard motor without sail in head wind. When she met a gust, the helmsman could not keep her course despite his steering effort and eventually the yacht suffered beam wind and waves from her port side. Then the yacht capsized toward starboard side. Although the windage area is small, the yacht could capsize because of insufficient righting arm due to crew weight on deck.

Two or three minutes passed with the turn turtle capsize and then the yacht re-righted up to an upright condition. When the yacht completely re-righted, she was almost even keel and flooded water was found in the cabin. The main difference between the two accidents is that the yacht in Osaka Bay capsized toward starboard side while the yacht in Lake Biwa did toward port side. Since the position of the bow hole is slightly shifted to the port side, the case of capsize toward port side the bow hole can be emerge with smaller additional wind-induced heel from turn turtle capsize. As a result, the yacht in Osaka Bay water ingress during the process from capsizing to re-righting could be smaller. The even keel at the re-righted moment also indicated small flooded water amount. It can be also pointed out that small roll damping at the capsized condition without sail could reduce time to re-right, which can limit water ingress.

7. CONCLUSIONS

As a result of hydrostatic calculations and model experiments from capsizing to sink, following conclusions were obtained:

- Because of so many crews on deck, the restoring arm of the yacht was drastically reduced.
- If the skipper failed to helm amidships and to release the main sheet in case of tacking about with the wind speed of 8 m/s or over, the yacht could capsize.
- If wind speed is more than 10 m/s, additional heel can allow air egress and water ingress. When the flooded water exceeds 2 m^3, the yacht could start to re-right.
- Because of the large amount of water inside, trim by the stern could occur and the companionway could submerge. If the bow hole is open, air egress through the bow hole and water ingress through the companionway could result in sinking of the yacht.
- The measured wind speed at the accident exceeds the above critical wind speeds for capsizing and re-righting.
- The outcomes could depend on the direction of capsizing because of offset of the position of the bow hole,

8. ACKNOWLEDGEMENTS

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