Considerations on the Metacentric Stability of Narrowboats

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In a recent discussion on the social media, the subject turned on taking a narrowboat along the lower tidal reaches of the London river – the Thames – it being suggested by several people that it was perfectly safe to do so and even to take such a boat across the English Channel to France. Let me be very clear about that. The modern live aboard narrowboat which developed from the cargo boats of the nineteenth and early twentieth century is a boat and suitable and safe only on the EU Category D calm waters of the canal and inland rivers and waterways not for the tidal reaches of a large river or the open seas of the English Channel which are EU Category C waters. See the Appendix 1 to this article. It also became clear in the discussion that many of the correspondents did not know anything about boat stability, one even suggesting that, because his boat had a flat bottom, she was stable.

Narrowboats have a relatively simple hull design with a long parallel mid body which may be of one of four cross sectional form. These forms are shown in Figure 1 below.

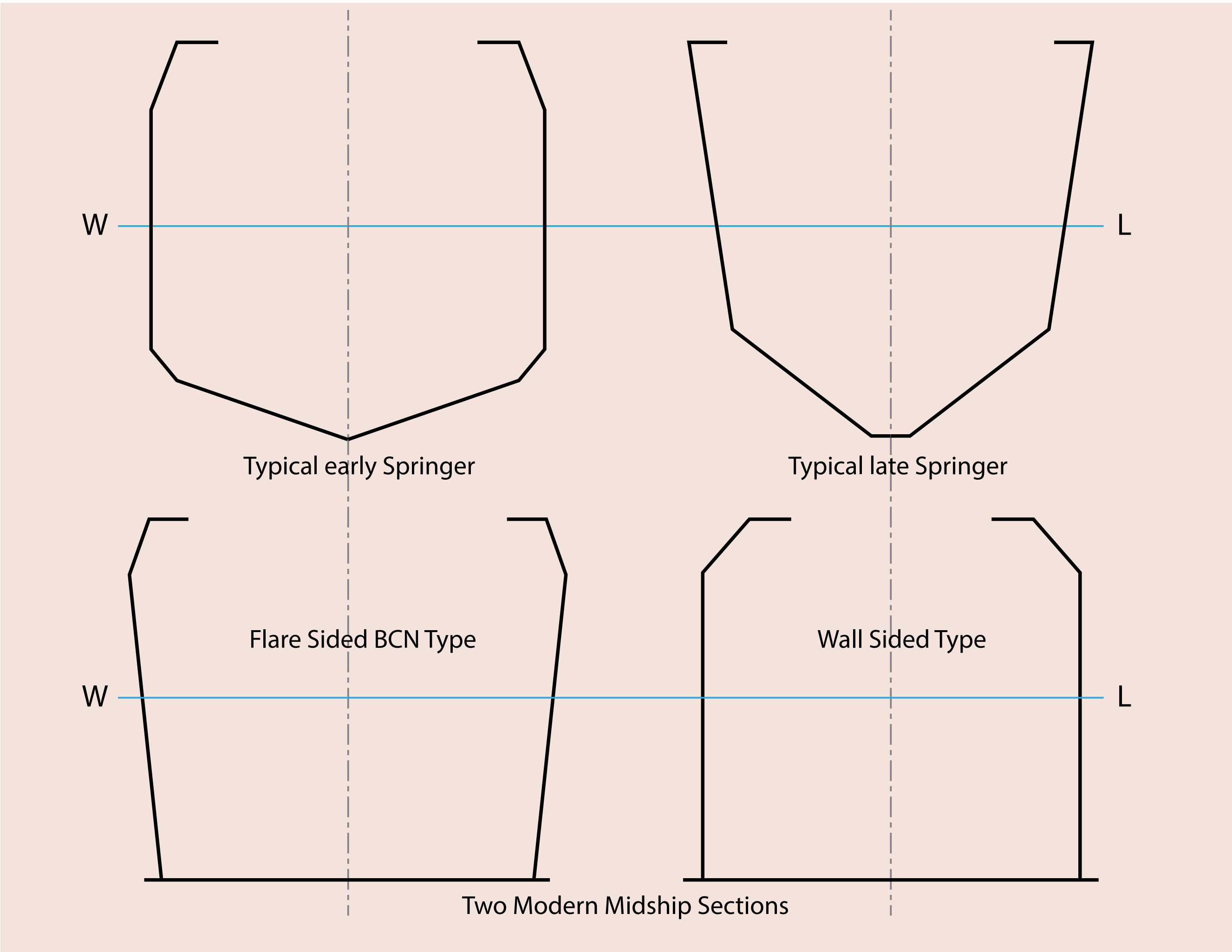

Figure 1. Typical narrowboat midship section outlines

The marine surveyor should note that the midship section bottom right in Figure 1 is said to be slab or wall sided NOT because the sides are called walls (they are, in fact, called sides) but because, like the walls in a house, they are flat and upright. The curved section forward of the parallel mid body is called the fore ship or entry and that abaft the after end of the parallel mid body is called the after ship or run.

When surveying such a boat, it is very important that the main and secondary dimensions of the hull be measured. The job takes about 5 minutes. The marine surveyor should remember that he is paid to record in his report items that he himself has measured, weighed, tested, whatever, NOT what somebody else has told him. So-called reported dimensions are not evidence, they are legally hearsay and usually undefined. In the event of the surveyor being sued, recording reported dimensions in his report would be a gift to the prosecuting counsel.

To illustrate the transverse metacentric stability of a narrowboat, the following dimensions for a typical modern vessel were chosen:

The boat's controlling dimension is the Breadth Overall which, in order to use the locks on much of the canal system, must not exceed six feet ten and a half inches or 2095 mm. The breadth that controls the stability of the boat, however, is that on the waterline which, after subtracting the thickness of any rubbing bars each side is usually about six feet eight and a half inches or 2040 mm but may be several mm less.

To understand why a ship or boat stays upright when afloat, it is necessary, first of all, to understand some naval architecture terms. Figure 2 shows the midship section of a narrowboat with wall sides. She is floating upright in still water. G is the centre of gravity and B the centre of buoyancy which is the geometric centre of the underwater form. G is vertically above B which, in turn, for most narrowboats is about 0.75 times the depth of the hull. G, for an average narrowboat is usually at or very close to the waterline and both B and G are on the boat's centreline. The weight of the boat and everything on her – the displacement and acting downward through the point G – is equal and opposite to the force of buoyancy acting upwards through the point B. Both are given the symbol Δ which is the Greek letter delta and corresponds to the English letter D.

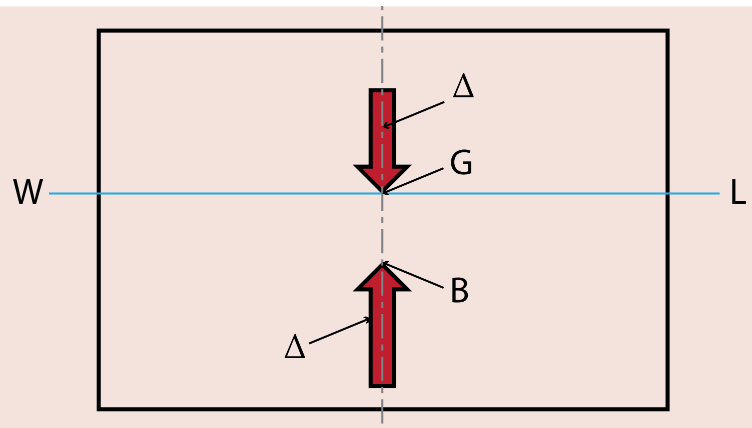

Figure 2
Initial Positions of Centres of Buoyancy and Gravity in Still Water

Item	Symbol	Dimensions Imperial	Dimensions Metric
Length Overall	L_{OA}	52′ 0″	15.85 m
Length Hull	L_{H}	50′ 0″	15.24 m
Length Waterline	L_{WL}	48′ 9″	14.86 m
Breadth Overall	B_{OA}	6′ 10½″	2095 mm
Breadth Waterline	B_{WL}	6′ 8½″	2045 mm
Depth Overall	D_{OA}	3′ 9″	1.14 m
Draught Forward	T_{F}	1′ 4″	0.41 m
Draught Aft	T_{A}	2′ 2″	0.66 m
Freeboard	f	2′ 0″	0.61 m
Displacement Weight	Δ	12.00 t	12.88 te
Displacement Volume	∇	432.00 ft^3	12.88 m^3
Block Coefficient	C_{B}	0.7922	0.7922

Table 1
Typical Narrowboat Dimensions

If now a small weight w kg is moved through a distance of d metres across the deck from port to starboard, the boat will heel to an angle of θ degrees. θ is the Greek letter theta and is pronounced as a soft th as in thin. See Figure 3 above. The underwater volume will remain the same, but its shape will alter. That will cause the centre of buoyancy to move to position B1. The weight of the boat will remain the same and will continues to act downward through the point G, but the buoyancy force, although it will remain the same in magnitude will now act upward through the point B1. The vertical line though the new centre of buoyancy will cross the centreline of the boat at the point M which is called the metacentre. The distance, GM is called the metacentric height and is measured in feet or metres and is the controlling factor of the boat's initial stability. The distance BM is called the metacentric radius and the distance GZ the righting lever.

The naval architect now has to use three formulae, all of which are fundamental to the study of ship stability.

The first which is proven using advanced mathematics states that:

$BM = I/\nabla$ m (1)

and the second, which is the fundamental formula of the Inclining Experiment, states that:

$GM = wd/\Delta.\tan\theta$ m (2)

The third states that:

$GM = KB + BM - KG$ m (3)

where

BM	= the metacentric radius	m
GM	= the metacentric height	m
KG	= height of the centre of gravity above the keel	m
I	= second moment of the waterplane area	m^4
d	= distance the inclining weights are moved	m
w	= inkling weight	kg
θ	= angle of heel	degrees
Δ	= vessel's displacement weight	kg
∇	= volume of displacement	m^3

Tan θ is a mathematical function and is obtained from either a booklet of mathematical tables or by pressing the appropriate button on a hand calculator.
∇ is pronounced Velta.

Of the items in the above list, all, except the second moment of area of the waterplane (I), can be measured directly. Textbooks on naval architecture give the method of computing I using the so-called Simpson's Rules although, these days, it is calculated using a standard computer program. For the marine surveyor at the bottom of a drydock such luxuries are not available, and he has to rely on a surprisingly accurate but very simple empirical formula which states that:

$I = C_W L_{WL}.B_{WL}^2/12C_B T_M$ m^4 (4)

where

C_W	= the coefficient of waterplane area	-
T_M	= the mean draught	m

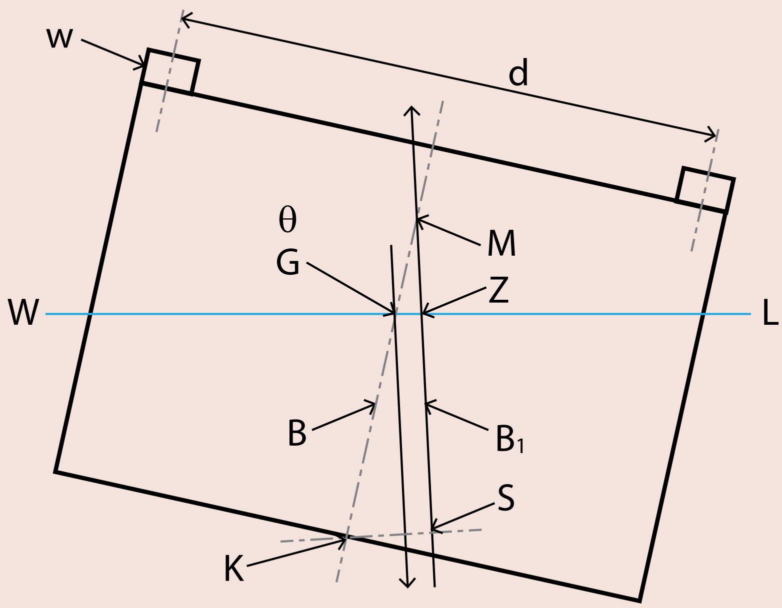

Figure 3
Vessel heeled due to Movement of Weight w.

The other symbols can be identified from Table 1.

For the narrowboat whose details are given in Table 1, the value of C_W which is the area of the waterplane divided by the waterline length and breadth was 0.8485 and may be assumed for most modern boats to be 0.85.

Now, using the above formulae and the data in Table 1 and taking the mean draught as:

$TM = (0.41 + 0.66)/2 = 0.535$ m

we calculate as follows:

from formula 4

$$I = \frac{0.8485 \times 14.86 \times 2.045^2}{12 \times 0.7922 \times 0.535} = 10.37 \quad m^4$$

And from formula 1:

$BM = 10.37/12.88 = 0.805$ m

Taking KG as 0.75 x 1.14, KB as 0.53 x 0.535 and using formula 3, we obtain:

$GM = 0.53 \times 0.535 + 0.805 - 0.75 \times 1.14 = \underline{\mathbf{0.23}}$ m

That is satisfactory and shows that the boat has a reasonably good initial stability.

As a matter of interest, naval architects use, as a preliminary design figure, an assumed value of GM to be 20% of the waterline breadth. The figure of 0.23 m for the above narrowboat is 11.25% of her waterline breadth.

As a simple check on the figure, it can be shown that the rolling period of a boat is a function of the metacentric height GM. The evaluation of a number of inclining and rolling tests according to various formulae showed that the following one gives the best results for GM estimation and that it has the advantage of being simple:

$$GM_o \approx k_{RP}(B_{WL}/T_R)^2 \quad \text{m} \qquad (5)$$

where

B_{WL}	=	waterline breadth	m
GM_o	=	the initial metacentric height	m
T_R	=	rolling period	s
k_{RP}	=	constant (the rolling coefficient)	-

The factor k_{RP} is of the greatest importance and it should be noted that the greater the distance of masses from the rolling axis, the greater the rolling coefficient will be. Therefore, it can be expected that:

- the rolling coefficient for an unloaded vessel (*i.e.* for a hollow body) will be higher than that for a loaded vessel.
- the rolling coefficient for a vessel carrying a great amount of fuel and ballast which latter is usually located in the bottom (*i.e.* far away from the rolling axis) will be higher than that of the same vessel having an empty fuel tank.

Experiments have shown that the results of the rolling test method get increasingly less reliable the nearer they approach metacentric height values of 0.2 m and below.

For a normal narrowboat, the coefficient k_{RP} can be taken to be about 0.45. The boat on the numerical example had a rolling period of 2.9 seconds so that, using the value for k_{RP} of 0.45, the metacentric height should be approximately:

$$GM = 0.45 \times (2.045/2.9)^2 = \underline{\mathbf{0.22}} \quad \text{m}$$

Which shows a very good agreement.

N.B.1 As a guide for the marine surveyor, if the rolling period in seconds is numerically greater than one and a half times the waterline breadth in metres, her stability should be considered very suspect.

N.B.2 The shape of the bottom of the boat is irrelevant,

The only realistic way of increasing the stability of the boat is to fit ballast as low as possible. A 10 mm thick bottom plate is very helpful in this respect.

The initial metacentric height, however, is only part of the stability problem. It applies up to a heel angle of about 5°. Above that angle of heel other factors have to be taken into account. As the heel increases, the righting lever GZ first increases up to a maximum at about a heel angle of 30° to 35° and the starts to decrease. At the angle at which the cockpit coaming touches the waterline, the GZ curve also called the Curve of Statical Stability takes a sudden plunger and rapidly becomes zero. At that point called the angle of vanishing stability or AVS the boat becomes totally unstable and will plunge sink rapidly. The angle at which the boat starts to flood called, unsurprisingly the minimum down flooding angle, is easily measured and should, in the author's opinion, be noted in his survey report.

Figure 4 below shows a typical curve of statical stability for a standard narrowboat and Figure 5 the minimum down flooding angle at the after cockpit and how to measure it.

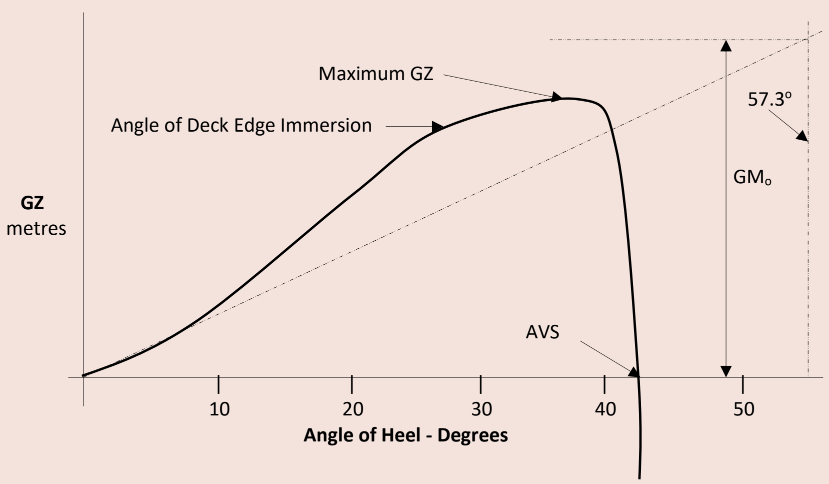

Figure 4
A Typical Narrowboat's Statical Stability Curve

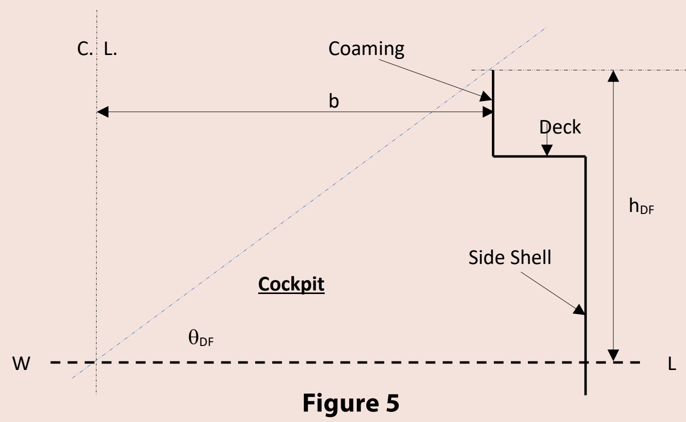

Figure 5
Down Flooding Height and Angle at Cockpit

In the Figure 5:

b =	half breadth of the cockpit	m
h_{DF} =	down flooding height at cockpit	m
θ_{DF} =	down flooding angle	degrees

Both b and h_{DF} are easily measured. B can be measured by taking the width of the cockpit and dividing that by 2. θ is obtained by dividing h_{DF} by b to obtain the tangent of that angle and then consulting a pocket calculator.

There are no rules covering privately owned narrowboats but, the nearest of the published rules are those for small commercial motor vessels, EU Category C waters it is recommended that they should be used as a guideline.

They are:

Minimum metacentric height	350 mm
Angle of maximum GZ value at least	25°
Maximum GZ value should be at least	200 mm at 30° or greater
Area under GZ curve to 30°	0.055 m.r
Area under GZ curve to 40°	0.090 m.r
Area under GZ curve between 30° 40°	0.030 m.r
Minimum down flooding angle	40°
A range of positive stability of at least (AVS)	60°

Most narrowboats cannot reach any of those criteria, except possibly the first and the third, hence the reason why they are confined to use on EU Category D waters.

The usual recommendation for down flooding angle is for the minimum to be 40o for a sea going boat. Again, a narrow boat is rarely able to reach that recommendation, but the author considers it to be good practice, when on a survey, for the marine surveyor to measure the down flooding heights and angles and report them. He should also measure the freeboard both sides and report both.

Strictly, the vessel may also down flood over a forward cockpit but, as the narrowboats usually trim by the stern, the after cockpit has a small down flooding height and angle. It is good practice to measure and report both forward and aft. Because of the trim, the measurements should be taken at the after end of both cockpits.

There are no rules applying to narrowboats that state what freeboard should be obtained but, again it is good practice, to compare the measured values to those proposed by the IIMS in the Unit 27 of their Surveying Diploma and repeated here verbatim.

- ***The freeboard is to be measured at mid hull length from the top of the side deck to the still waterline and should be at least 530 mm for a vessel 12 metres hull length and 685 mm for a vessel 22 m hull length. Freeboards for intermediate lengths to be by direct interpolation.***

  Again, many boats will not reach that standard, and the freeboards should be simply reported without comment.

  If possible, the marine surveyor should also carry out a simple rolling test on the boat and report the results. See Appendix 2.

  N.B.3. The marine surveyor should also note that narrowboats are single compartment vessels. That is, they have a single bulkhead at each end of the main cabin neither of which are strictly water tight. It takes, therefore, only the single cabin between those bulkheads to be breached open to the sea for her to plunge sink.

The dangers of overplating an area of the hull have been discussed elsewhere and will not be considered further here except to state that, bearing in mind the Law of Unconsidered Consequences which is so often overlooked, one of the side effects of overplating is the changes that the practice have on the boat's transverse metacentric stability. The extra plating adds approximately 7 kg per square metre of area per mm of thickness to the hull and that has a deleterious effect on the height of the centre of gravity, it also alters the metacentric radius, the height of the centre of buoyancy, reduces the area under the statical stability curve, the maximum GZ value and the angle at which it occurs, reduces the AVS and also reduces both the down flooding height and angle. If carried out, it should, therefore, only be done with careful thought and with such effects taken into account.

Considerations on the Metacentric Stability of Narrowboats

APPENDIX 1

DEFINITIONS OF SEA AREAS

(From the Official Journal of the European Union)

Article 1 of the **European Directive (94/25/EC)** dated **16th June, 1994** defines recreational craft as "…. any boat, of any type, regardless of the means of propulsion, from 2.50 metres to 24.00 metres hull length, measured according to the appropriate harmonised standards, intended for sports and leisure purposes." The significant wave height is defined as the average height of the 1/3 highest waves and a number of the waves experienced may be up to twice that height.

Category Definitions

A. OCEAN: Vessels designed for extended voyages where conditions may exceed wind force 8 (Beaufort Scale) and significant wave heights of 4 metres and above may be experienced and vessels largely self sufficient.

B. OFFSHORE: Vessels designed for offshore voyages where conditions up to, and including, wind force 8 (Beaufort Scale) and significant wave heights up to, and including, 4 metres may be experienced.

C. INSHORE: Vessels designed for voyages in coastal waters, large bays, estuaries, lakes and rivers where conditions up to, and including, wind force 6 (Beaufort Scale) and significant wave heights up to, and including, 2 metres may be experienced.

D. SHELTERED WATERS: Vessels designed for voyages on small lakes, rivers and canals where conditions up to, and including, wind force 4 (Beaufort Scale) and significant wave heights up to, and including, 0.5 metres may be experienced.

Categorisation of Waters by the U.K. Maritime and Coastguard Agency MSN 1719(M)

These categorisations strictly apply only to Class IV and V Passengers Vessels and determine which waters are NOT regarded as 'seas'.

Category A: Narrow rivers and canals where the depth of water is less than 1.5 metres and where the significant wave height could not be expected to exceed 0.6 metres at any time.

Category B: Wider rivers and canals where the depth of water is generally more than 1.5 metres and where the significant wave height could not be expected to exceed 0.6 metres at any time.

Category C: Tidal rivers and estuaries and large, deep lakes and lochs where the significant wave height could not be expected to exceed 1.2 metres at any time.

Category D: Tidal rivers and estuaries where the significant wave height could not be expected to exceed 2.0 metres at any time.

N.B.4. The Port of London Authority (Safety Bulletin No 1/2012) has recommended that the tidal reaches of the river Thames which stretch from Teddington Lock to the Number One Sea buoy be regarded as MCA Category C waters as wave heights of up to 1.2 m may be encountered there. The author would also **recommend** that the similar tidal reaches of the river Medway be so classified.

Narrow boats with engine room side ventilation holes particularly are not suitable for operation on these waters.

Considerations on the Metacentric Stability of Narrowboats

APPENDIX 2

AN APPROXIMATE DETERMINATION OF A SMALL VESSEL'S STABILITY BY MEANS OF THE ROLLING PERIOD TESTS

(From the Official Journal of the European Union)

The Rolling Period Method

As a supplement to the approved stability information, the initial stability can be approximately determined by means of a rolling period test. Vessels with a high initial stability are said to be stiff and have a short rolling period and conversely, vessels with a low initial stability are said to be tender and have a long rolling period. The following guidance notes describe the rolling period test procedure which can be performed at any time by the crew of a small vessel.

1. The test should be conducted in smooth water with the mooring lines slack and the vessel breasted off to avoid making any contact during the operation. Care should be taken to ensure that there is a reasonable clearance of water under the keel and the sides of the vessel.

2. The vessel is made to roll. That can, for example, be done by leaning on the nearest gunwale when it is at its highest point and taking one's weight off as soon as the boat starts to move downward.

3. The timing and counting of the oscillations should only begin when it is judged that the vessel is rolling freely and naturally and only as much as it is necessary to accurately time and count these oscillations (approximately 2° - 6° to each side).

4. With the vessel at the extreme end of the roll to one side (say port) and the vessel about to move toward the upright, one complete oscillation will have been made when the vessel has moved right across to the other extreme side (*i.e.* starboard) and returned to the original starting point and is about to commence the next roll.

5. By means of a stop watch, the time should be taken for not less than six of the complete oscillations. The counting of these oscillations should begin when the vessel is at extreme end of a roll.

6. After allowing the roll to completely fade away, the operation should be repeated at least twice more. Knowing the total time for the total number of oscillations made, the time for one complete oscillation, say T seconds, can be calculated.

7. The boat's metacentric height can then be estimated using formula 5 above.