TESTING THE TRANSIENT CAPSIZE DIAGRAM CONCEPT

By

Prof. D. Vassalos*, Dr. K. Spyrou+ and Dr. N. Umeda++
*Director of The Ship Stability Research Centre, University of Strathclyde, UK
+Research Fellow, Centre for Non-Linear Dynamics, UCL, UK
++Head of Ship Performance Section, Nat. Research Inst. of Fisheries Eng., Japan

SUMMARY

This brief note describes an attempt to test the validity and provide corroborative evidence of the *Transient Capsize Diagram* concept, a methodology proposed by Rainey and Thompson, for developing stability criteria based on chaotic dynamics. This entails the undertaking of a series of capsizing experiments in beam seas in the manoeuvring basin of the National Research institute of Fisheries Engineering in Japan, using a 1/17.5 scale model of a purse-seiner.

1. BACKGROUND

In simple terms, Thompson and his colleagues, [1]-[3], have studied the problem of a driven mechanical oscillator given by

$$\ddot{\phi} + \beta\dot{\phi} + \phi - \phi^2 = M \sin(\omega t + \varepsilon)$$

This equation is assumed to represent the roll motion of a ship subjected to a beam seas excitation moment M at frequency ω (ε in their studies was taken fixed at 180° with linear damping β at 0.1). The only non-linearity of parabolic restoring implies a softening spring with an underlying total potential energy that has a minimum in the upright state and a maximum at the vanishing angle beyond which the ship can capsize. In this respect, and in the relevant jargon, the problem of ship capsize is a straightforward example of an escape from a potential well.

Considering the above, the four-dimensional *phase-control space* spanned by $\{\dot{\phi}(0), \phi(0), M, \omega\}$ defines the ensuing roll motion.

In a slowly evolving sea state, implying *steady-state* behaviour, the ship motion may be summarised using a *steady-state bifurcation* diagram, Figure 1, which can be derived by tracing the steady states as one of the control parameters, say M, is slowly varied. Steady states can invariably undergo various complicated bifurcations, including jumps to resonance, subharmonic oscillations, chaotic behaviour and ultimately capsize. Repeating this procedure at different ω values, a capsizal boundary can, therefore, be determined, Figure 2. It is conjectured that all of these can add to the overall understanding of ship behaviour and stability.

In assessing the engineering significance of such investigations the team at UCL concluded that it is too cumbersome and time consuming and, much more to the point, unnecessary and irrelevant. Instead, they rightly propose that in a noisy environment, it is more relevant and simpler to focus attention on *transient* behaviour. This would correspond to a short pulse of regular waves, such as a wave group, impinging upon the ship in otherwise relatively calm weather conditions. This is thought to be a worst-case scenario and a more realistic representation of a sea state than a long train of regular waves. In this case, a *transient safe basin* is defined, containing the set of points in the *phase-control space* referred to above that do not escape (lead to capsize) within a number of forcing cycles, typically 8. At each case, defined fully by the initial conditions in the $\{\dot{\phi}(0), \phi(0)\}$ plane under specified controls (M,ω), all interest is focused on the binary outcome of capsize-non-capsize, making no note of the steady states onto which the non-capsizing motions might settle.

In exploring *transient safe basins*, an important finding offered a platform for the team to propose what they termed a *transient capsize diagram*, Figure 3, as a possible means for developing ship stability criteria. It was observed that, for a given frequency, the erosion of the safe basin is sudden, dramatic and from the centre when a critical level of excitation (wave height) is reached, Figure 4. It was concluded, therefore, that a critical wave height could be determined through either a physical or a numerical experiment by examining transient motions from <u>any</u> initial condition and by implication non other more convenient that the upright equilibrium position. In essence, therefore, the system behaviour was studied by taking <u>all</u> possible initial conditions, in order to ensure that any sensitivity of the non-linear system to such conditions will be catered for, only to find out that ship capsizal resistance is essentially independent of which position the vessel found herself when an extreme critical wave hit her.

Such a wave, determined in turn for a range of relevant frequencies, could be used as an index of *capsizal resistance* for the vessel in question. By linking, finally, the (*steepness, wave period*) loci in the transient capsize diagram to a weather data for a given area of operation, capsizal probabilities can be established, Figure 5.

Summarising the work at UCL concerning the above, the following points are considered to be noteworthy in relation to the problem of ship capsize:

- As a concept, the *transient capsize diagram* is very simple and powerful, and could find application in addressing more practical ship stability problems. Ship stability in beam seas is a problem only for small vessels, which could simply be overturned by large breaking waves, Dahle [5]. The majority of capsizings occur in astern seas, Kan [4], as a result of pure loss of stability, parametric resonance and broaching-to, all of which require a different level of conceptual, mathematical and physical description.

- The reason for the above known fact derives from the favourable phasing between heave and roll motions with most ship hulls. This natural attribute of a ship hull is indeed a serious omission in the mathematical model considered and a similar claim can be made on behalf of sway. Considering a coupled non-linear three degrees of freedom model, however, would mean that a 6D phase-space would have to be considered. A crude reminder of how difficult it is to represent reality realistically!

2. VESSEL/MODEL PARTICULARS

The design condition considered in these tests corresponds to the loaded departure condition, the details for which are given in Table 1. The vessel in question is fitted with bilge keels having the following particulars:

$d_{bk} = 0.35m$; $l_{bk} = 14.56m$

The bilge keels are positioned between frames 17-45 (constant frame spacing of 0.52m).

Table 1: Model/Vessel Particulars

Parameter	Vessel	Model (Scale=1/17.25)
Loa	43.00m	2.493m
Lbp	34.50m	2.000m
B	7.60m	0.441m
D	3.07m	0.178m
df	2.84m	0.165m
da	3.14m	0.182m
θ	0.5°	-
Cb	0.652	-
Δ(fresh water)	511.2 tonnes	99.63kg
LCG	-1.741m	-0.101m
Vs	7.355m/s	1.758m/s
KG	3.42m	-
GM	0.755m	-
Tϕ	7.47sec	-

4. MODEL EXPERIMENTS

Capsizing experiments were undertaken in beam seas for the following reasons:

- The manoeuvring basin at NRIFE is not equipped with model position tracking system which is considered to be essential for capsizing tests in astern seas to be used effectively to validate computer simulation programs.

- Capsizing tests in beam seas are easier to perform (or so it was thought) and could fit within the limited period available.

As it turned out, it was necessary to change plans more than once, to produce something meaningful, even with regular wave testing in beam seas. More specifically, the following capsizing experiments were carried out.

Model with bulwark

Observation of a limited number of tests and ensuing model capsizings have led to the conclusion that the principal cause of capsize of the test model was due to the progressive accumulation of water on deck. This phenomenon is particularly difficult to model, on the one hand and, on the other, it is not taken into account in the theoretical work these model tests were aimed to corroborate.

Model without bulwark

As a consequence of the above, the bulwark was subsequently removed from the test model and sample tests performed. In this case, as a result of deck edge submergence, the roll damping of the model was increased substantially beyond the normal level for ships and no capsize was possible, even in the most extreme waves that could be generated by the manoeuvring basin, which in realistic terms were far too severe for the model in question.

Model without bulwark and reduced GM

Following the above, a number of options were discussed in order to progress further, before deciding that the most suitable option, still allowing for corroborative evidence to be produced, was to reduce the metacentric height (GM) of the model. Indeed, following a 30% reduction in GM, successful capsize experiments were undertaken and capsize boundaries in terms of wave heights established in representative wave lengths. As shown below:

Capsizing Model Tests in Beam Seas

- No 307 : Capsizing of model with bulwark at H / λ =1/20; f=0.968 Hz.
- No 321 : Capsizing of model without bulwark and reduced GM at H / λ =1/12; f=0.527 Hz.

5. CONCLUDING REMARKS

Deriving from the above, and taking into consideration the scarcity of experimental evidence linking chaotic dynamics with ship motion dynamics, it could be said that work in this area has not advanced to the point where material of substance could be offered to the practising Naval Architect to enhance or ensure ship safety. Some innovative concepts, however, appear to hold promise for achieving further advances in the field of ship stability but substantial development might be needed together with attempts to link these ideas to the practical ship stability problem.

7. . REFERENCES

[1] THOMPSON, J.M.T. and SOLIMAN, M.S., "Fractal Control Boundaries of Driven Oscillators and their Relevance to Safe Engineering Design", Proc. R. Soc. Lond. A 428, 1-13, 1990.

[2] SOLIMAN, M.S., "An Analysis of Ship Stability Based on Transient Motions", STAB'90, Naples, Italy.

[3] RAINEY R.C.T. and THOMPSON J.M.T., "The Transient Capsize Diagram - A New Method of Quantifying Stability in Waves", JSR, Vol. 35, No 1, March 1991.

[4] KAN, M., SARUTA, T. and TAGUCHI, H., "Capsizing of a Ship in Quartering Waves", Trans. JSNA, Vols 167-8, 1990.

[5] DAHLE, E.A., MYRHAUG, D. and DAHL, S.J., "Probability of Capsizing in Steep and High Waves from Side in Open Sea and Coastal Waters", Ocean Engineering, Vol. 15, No 2, 1988.

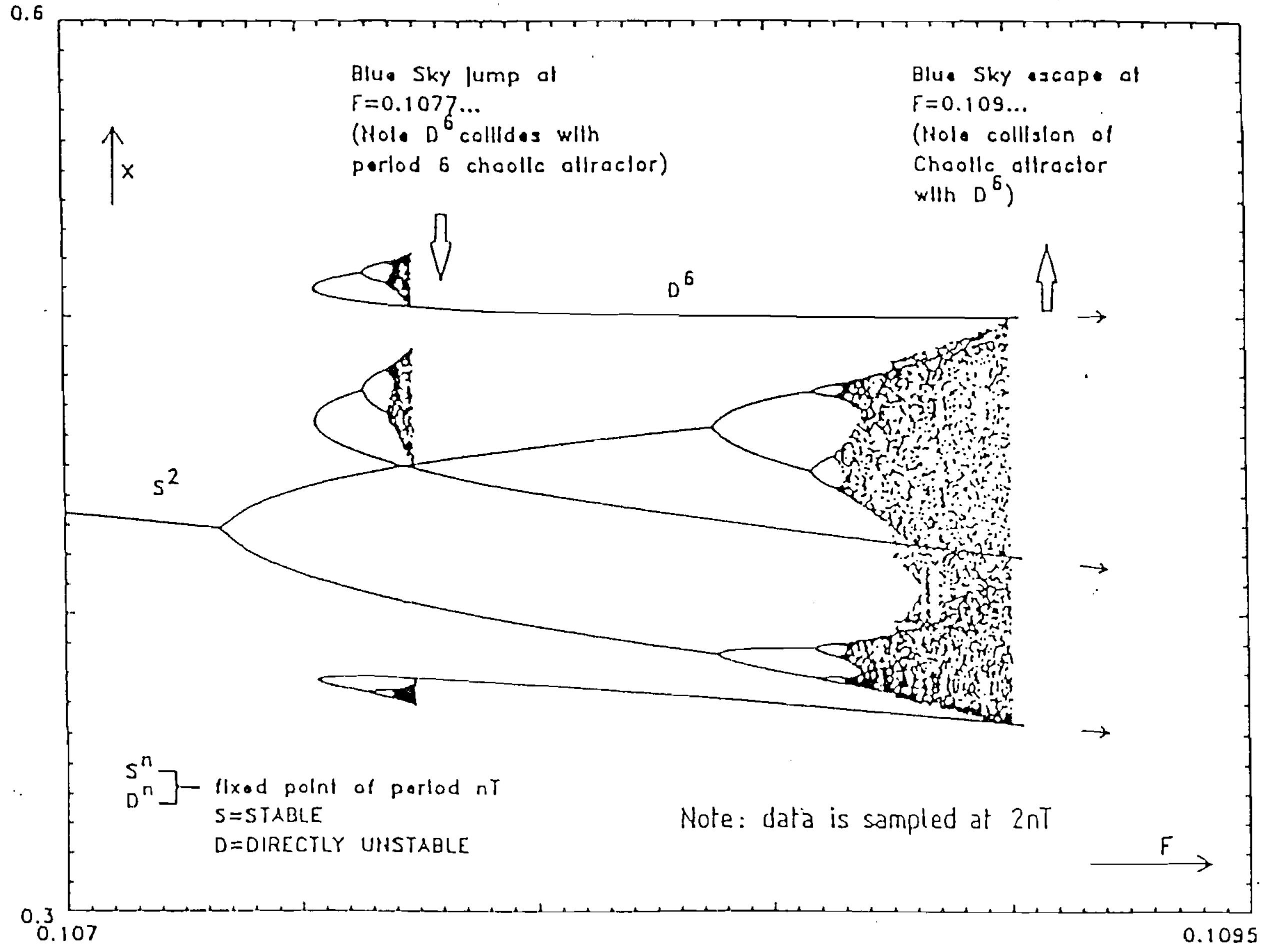

Fig 1: Evolution of daughter attractors with increasing wave height: the horizontal axis is wave height; the vertical axis is the stroboscopically sampled horizontal coordinate of the attractors in phase space. The excitation frequency is 0.85 times the natural frequency of small roll motions, and the damping of such motions is 5 percent critical.

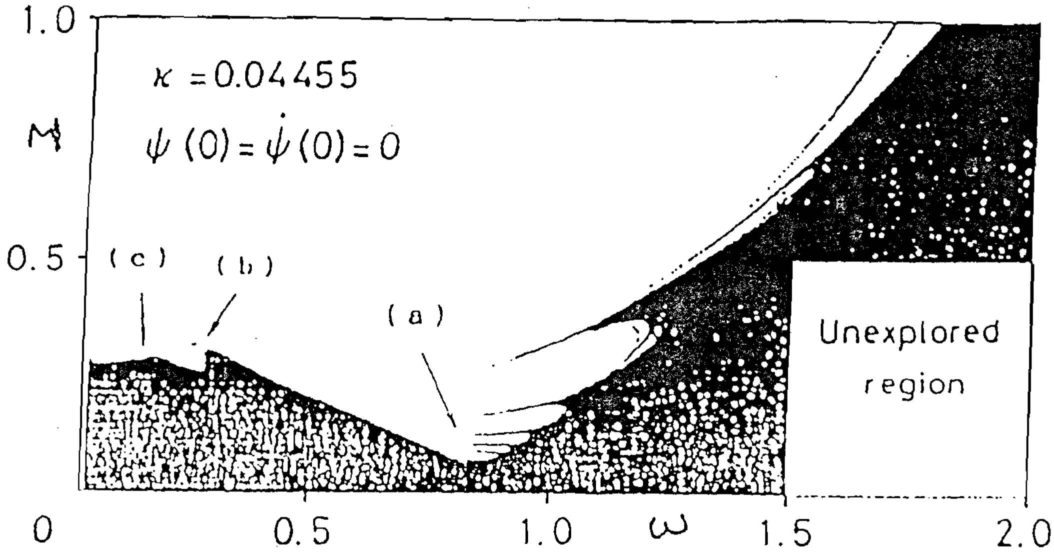

Fig 2: Fractal boundary of safe area in m-ω control space.

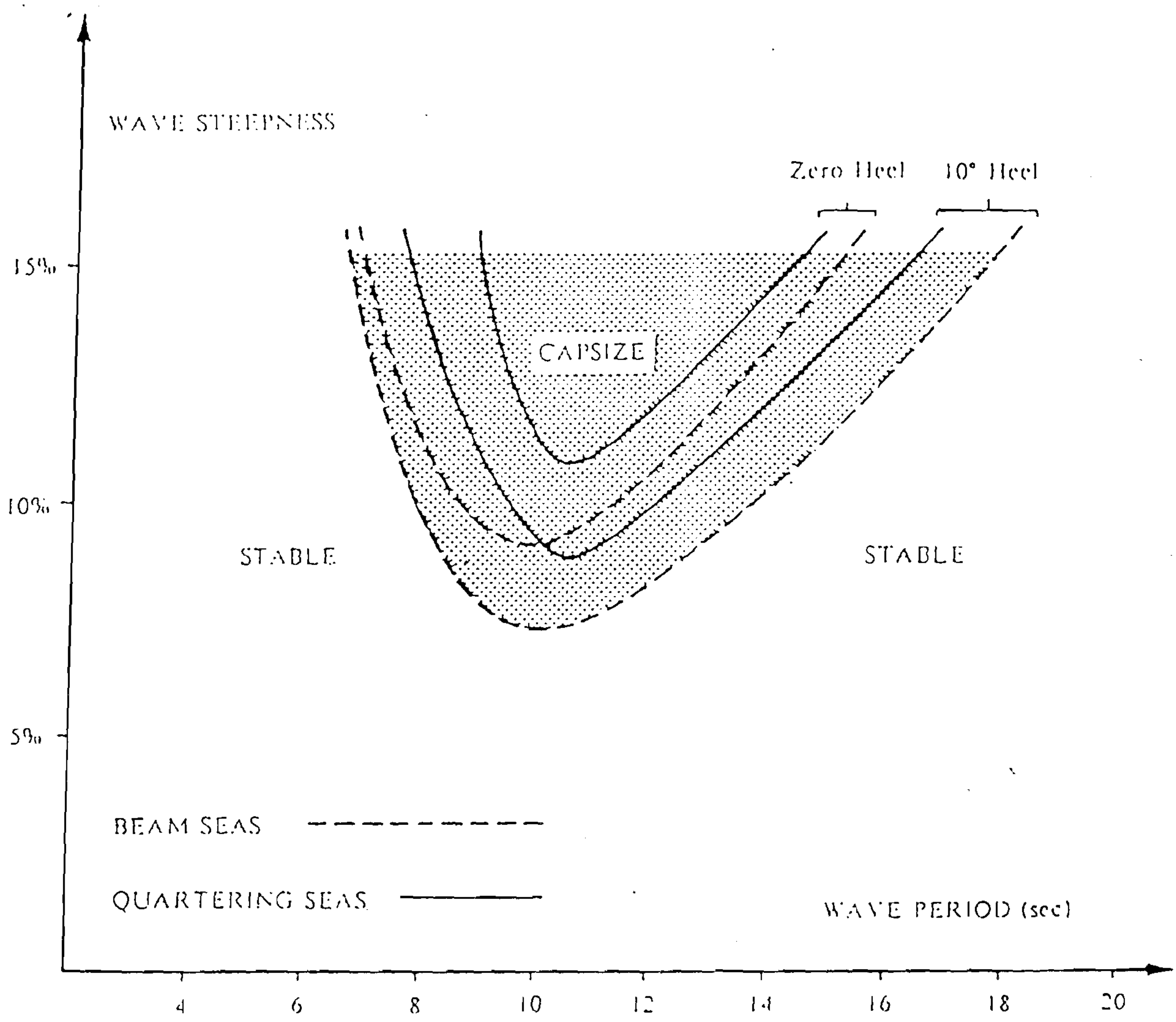

Fig 3: Typical transient capsize diagram.

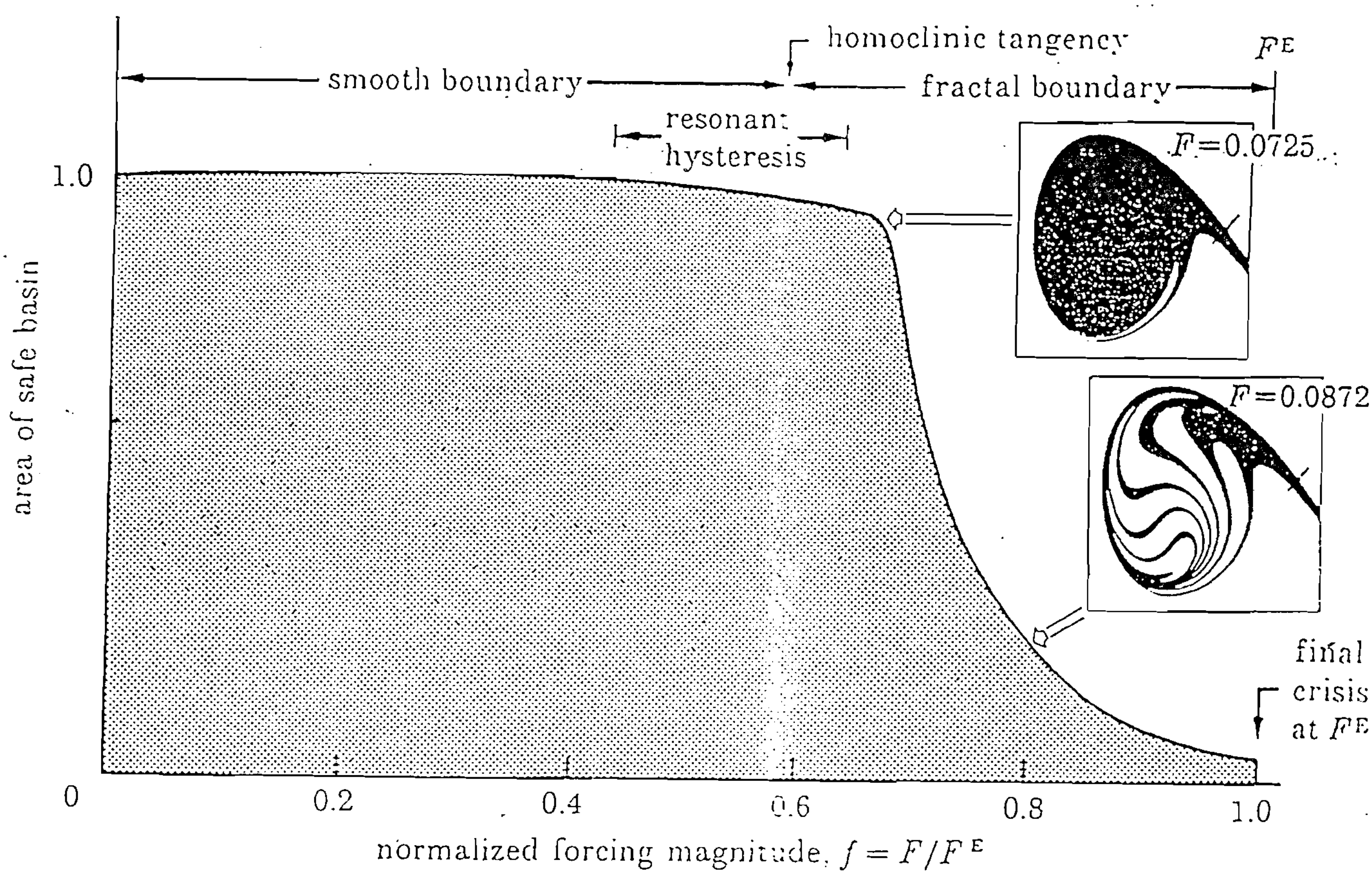

Fig 4: Loss of engineering integrity due to erosion of the safe basin of attraction. The normalized area of the safe basin, within a window, is plotted against the normalised forcing magnitude. Based on high-precision computations by Yoshisuke Ueda.

Standard Wave Diagram for the North Pacific(All Year)

All year (554945)

Group N buoys												Total
14.75	0	0	0	0	0	0	0	0	0	1	0	1
13.75	0	0	0	0	0	0	0	0	3	0	0	3
12.75	0	0	0	0	0	0	0	2	13	2	1	18
11.75	0	0	0	0	0	0	2	18	12	2	0	34
10.75	0	0	0	0	0	2	21	58	10	2	0	92
9.75	0	0	0	0	0	6	137	79	25	5	0	252
8.75	0	0	0	0	1	152	370	113	33	6	1	675
7.75	0	0	0	0	77	828	582	178	59	10	2	1736
6.75	0	0	0	11	931	1919	845	216	49	9	2	3982
5.75	0	0	2	600	4367	3103	1127	262	43	8	5	9515
4.75	0	0	201	6204	9234	4473.	1368	305	70	28	11	21893
3.75	3	28	5293	19238	12949	5283	1576	375	124	43	9	44921
2.75	37	3361	26811	27262	13581	5241	1520	413	133	26	7	78394
1.75	2094	32782	43541	25961	10896	3607	1082	332	95	16	2	120408
0.75	16740	45949	32292	12330	3505	1040	246	69	16	2	0	112188
0	1759	2577	1206	286	53	6	1	0	0	0	0	5889
Total	20634	84696	109345	91892	55592	25659	8876	2421	685	159	40	400000
Period	0	5	6	7	8	9	10	11	12	13	14	

Fig 5: Probabilistic transient capsize diagram.