26ο Θερινό Σχολείο – Συνέδριο «Δυναμικά Συστήματα & Πολυπλοκότητα»
Εθνικό Μετσόβιο Πολυτεχνείο
15-19 Ιουλίου 2019

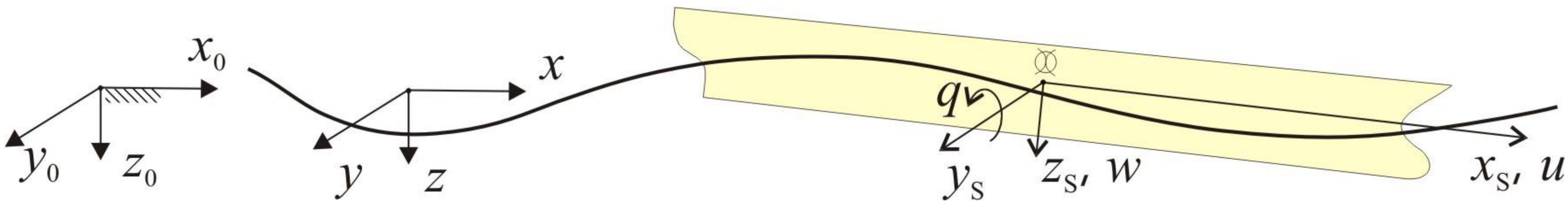
Ομοκλινικές συνδέσεις και η επίδρασή τους στην ασφάλεια πλοίων

Κώστας Σπύρου

Σχολή Ναυπηγών Μηχανολόγων Μηχανικών
Εθνικού Μετσοβίου Πολυτεχνείου

16 Ιουλίου 2019

Philosophy of approaches for predicting ship behavior at sea



Target: Ordinary behavior

Emphasis: Accurate modeling

Propulsion/environmental efficiency economy, comfort

Features:

- ✓ Quantitative – ship geometry
- ✓ "First principles" hydrodynamics
- ✓ Mildly nonlinear
- ✓ Few simulations
- ✓ Time domain analysis

Target: Extremes, limits of safe behavior

Emphasis: Ship motion phenomena

Capsize, surf-riding, directional instability, parametric rolling, sudden heel during loading or due to symmetric water entry (loll), oscillations of moored vessels, sub-harmonic & chaotic motions

Features:

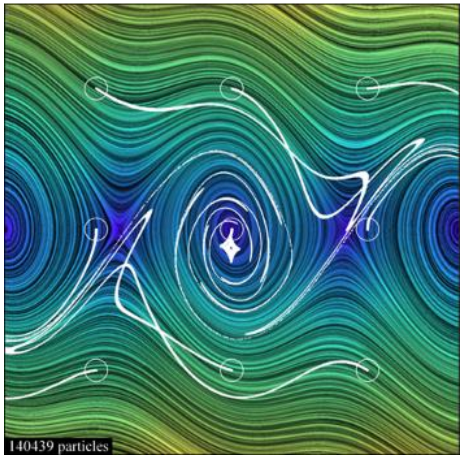
- ✓ Intuitive modeling - low-dimensional model approximations
- ✓ Ideal for understanding effect of nonlinearities
- ✓ Holistic in the dynamics
- ✓ Good for safety criteria development
- ✓ Analysis in *phase space*

Combines:

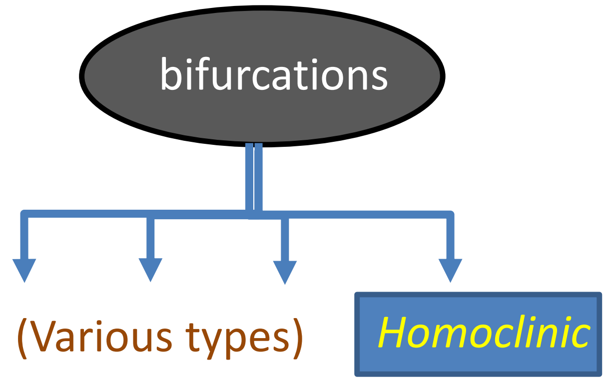
- Ship hydrodynamics
- Nonlinear dynamics – stability theory
- Stochastic dynamics

The phase-space

Motions seen as a “flow” in the *phase-space*



For a nonlinear system, phase flow’s geometry can be qualitatively changed as some influential parameter is varied

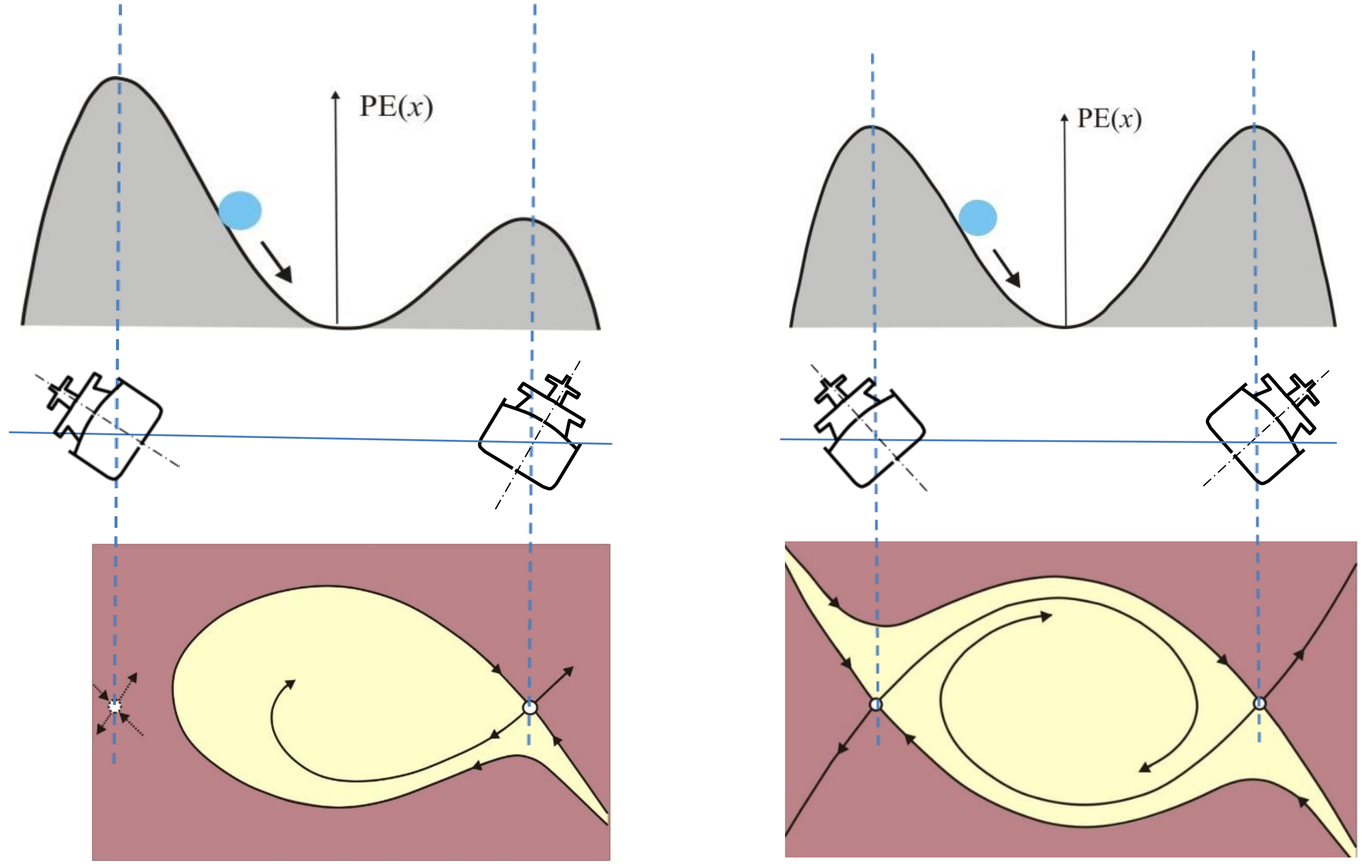


- ***Homoclinic***: phenomena triggered by the contact of invariant manifolds – formation of homoclinic or heteroclinic curves on Poincaré section of phase flow
- They modify globally the phase-space layout (change not in small neighborhood)
- Relate with **dynamic instabilities** – IMO’s 2nd *Generation Ship Stability Criteria address homoclinic phenomena*
- Can explain unusual ship motions

Typical manifestations ⇒
- abrupt disappearance of periodic behavior
- connected with ship capsize
- introduce motion irregularity

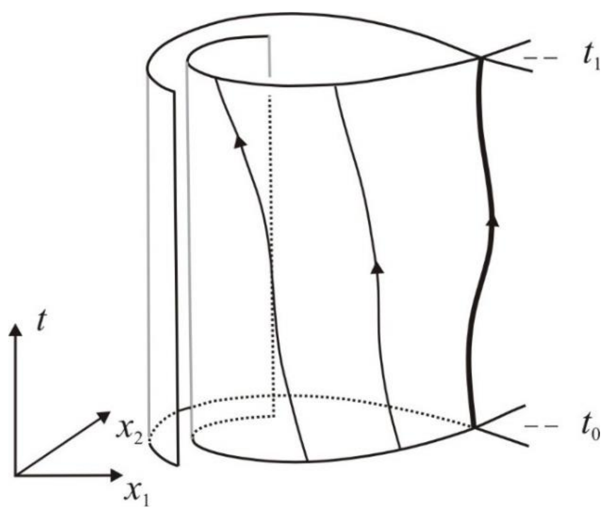
Essential concepts introduced through a ship’s roll motion

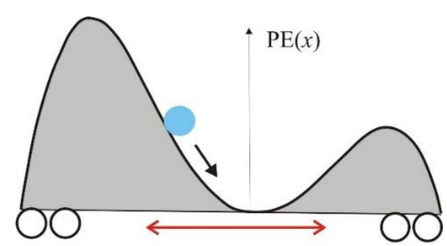
Energy dissipating system



The basin (domain) of attraction

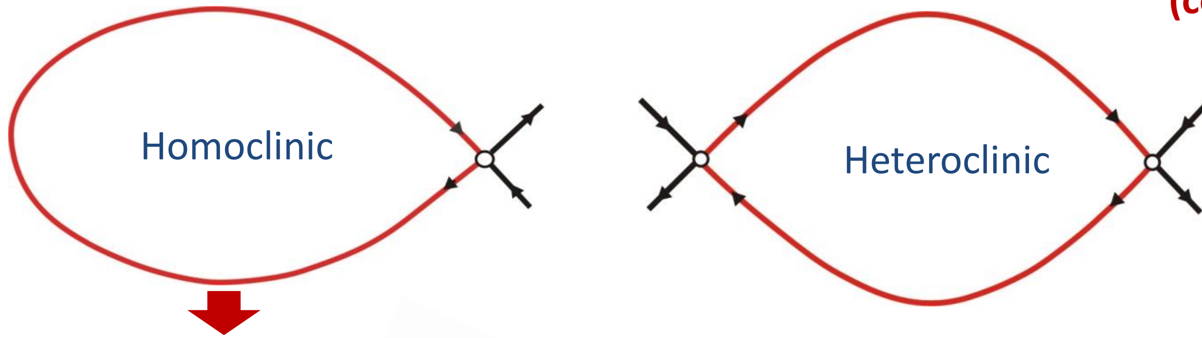
Externally excited system

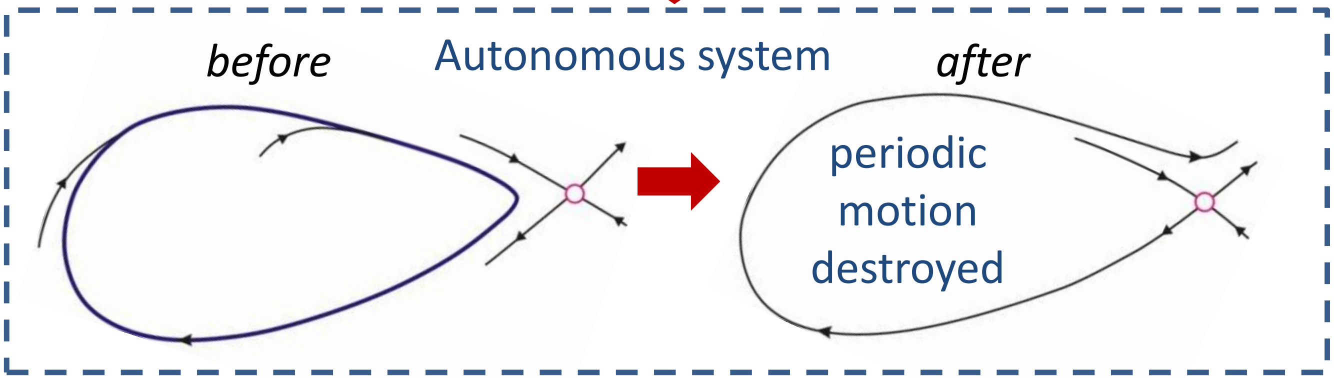




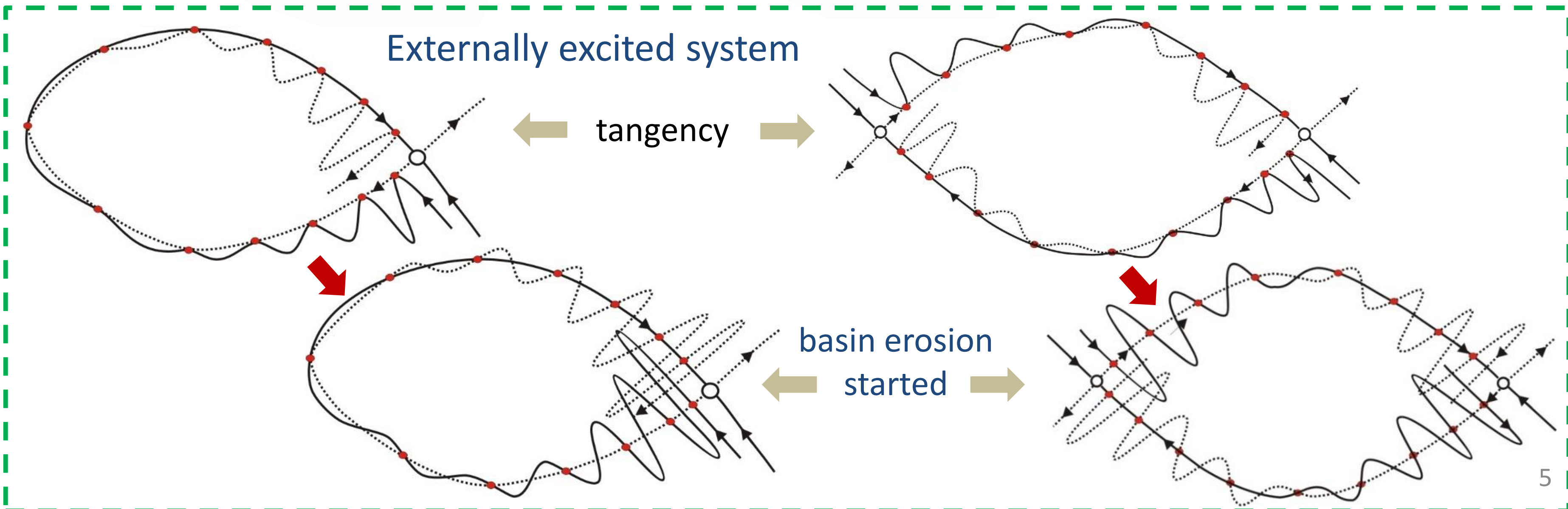
Essential concepts (cont'd)

Formation of *homoclinic* curves





Homoclinic saddle connection



Prediction tools

Direct simulation (= blind search)

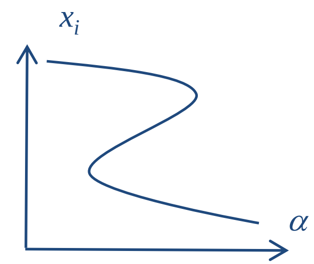
Continuation (path - following): suitable for deterministic systems
Keller (1978), Rheinboldt (1980), Kubicek & Marek (1983), Doedel & Kernevez (1986), …

Melnikov's method: semi-analytical - monitoring distance of invariant manifolds (for deterministic and stochastic systems)
Melnikov 1963, Wiggins 1990, Frey & Simiu 1993, …
Works also as "energy balance" *(Thompson 1997)*

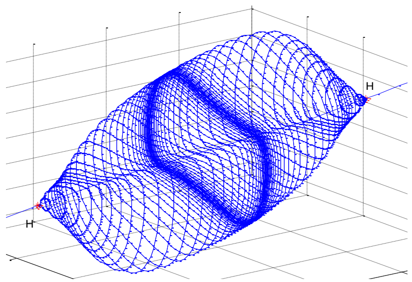
Lagrangian coherent structures: field methods

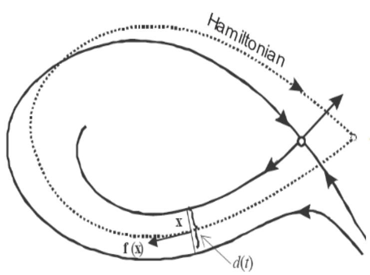
- Finite-time Lyapounov exponents (FTLE)
  Haller & Yuan (2000), Shadden, (2011) …
- Finite-size Lyapounov exponents (FSLE)
  Artale et al. (1997), Koh & Legras (2002) …
- Variational method
  Haller (2011)
- Extraction of coherent sets via clustering
  Froyland & Padberg-Gehle 2015

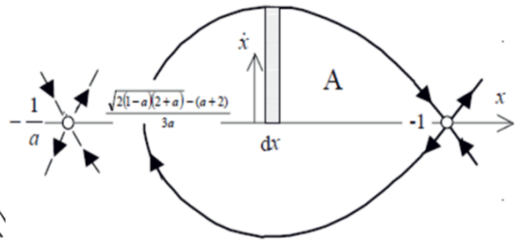
Continuation of equilibria

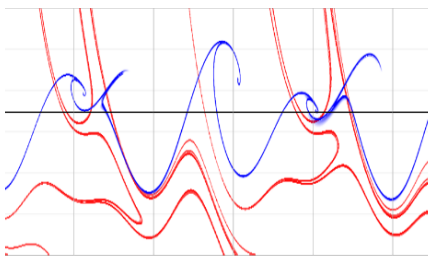


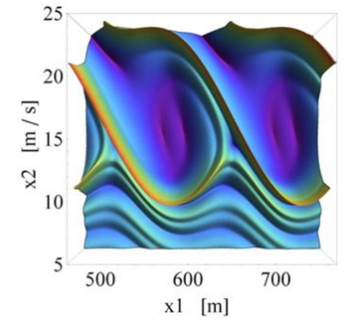
Continuation of limit-cycles











Summary of *homoclinic* phenomena in ship motions

Unforced ship:

→ Heteroclinic saddle connection modifies the **boundary of free rolling**, as heel bias is strengthened.

Regular waves:

- Beam-seas: Homoclinic and/or heteroclinic intersections enable **capsize**
- Following/quartering seas:

→ Homoclinic saddle connection leads to **global surf-riding and possibly to broaching-to**

→ Homoclinic saddle connection ends **oscillatory surf-riding** on wave down-slope.

Multi-chromatic/stochastic waves:

- Following/quartering seas:

→ Heteroclinic intersections increase susceptibility for **broaching-to**.

Wind loading:

- Beam wind

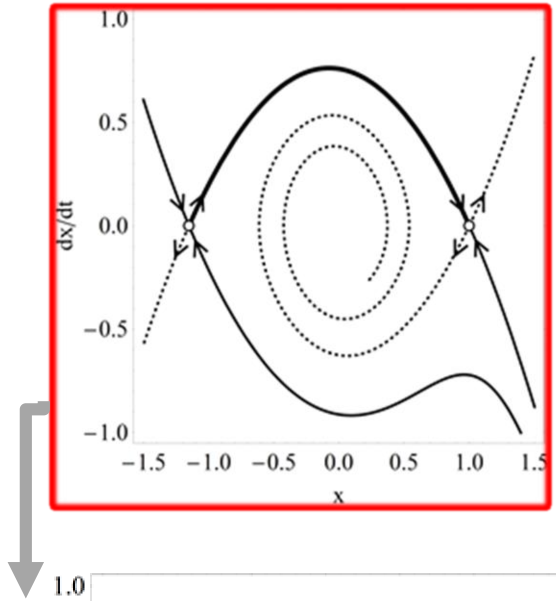
→ Homoclinic to saddle-node (omega explosion): barrier between **straight-line motion** and **turning**.

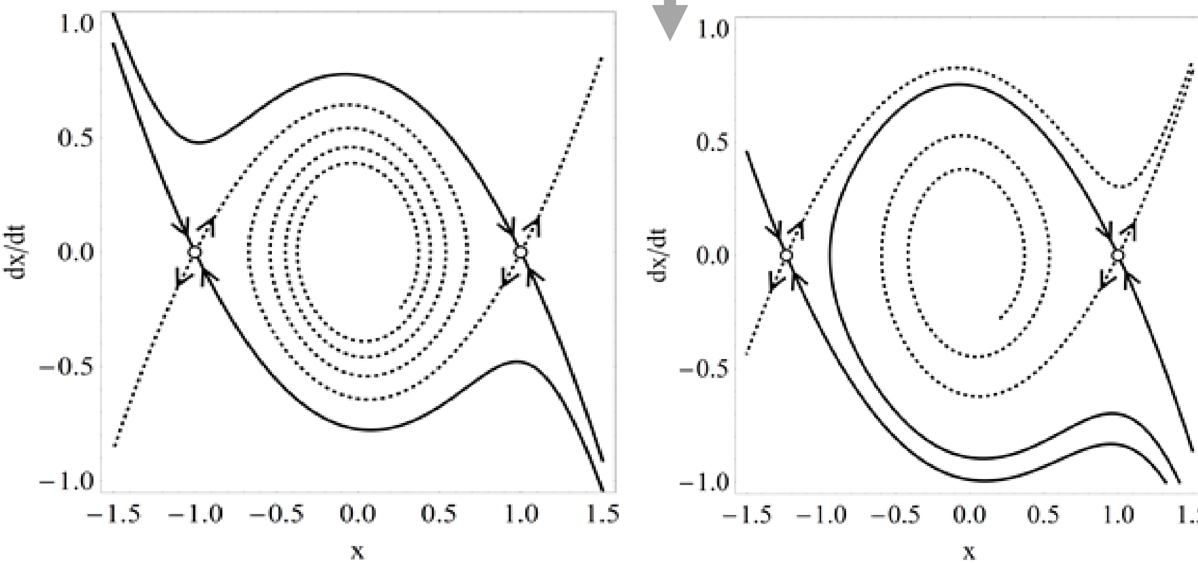
- Head wind:

→ Homoclinic saddle connection ends **yaw oscillations** (ship heading into wind with sluggish rudder control.

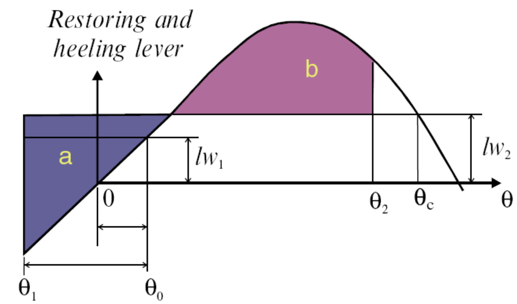
The roll motion

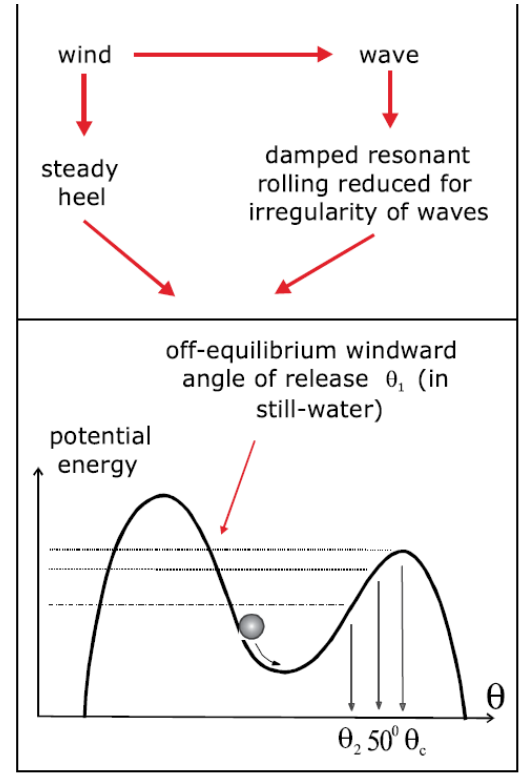
a) Unforced case





The “weather criterion”





Basic (normalized) model for rolling with heel bias

$$\ddot{x}+b_1\dot{x}+b_3\dot{x}^3+x-(1-a)x^2-ax^3=f\sin\Omega t$$

(2002) JSR, 46/3

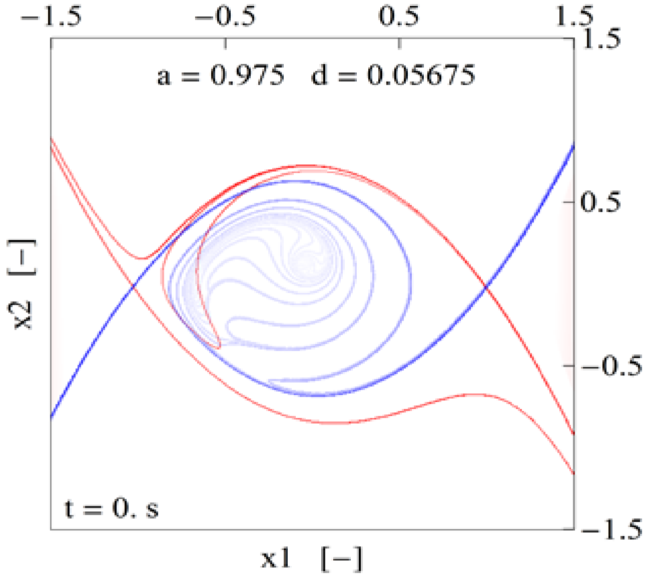
Melnikov prediction: heteroclinic curve formed at: $a=1-\sqrt{2}\,b_1-\dfrac{12\sqrt{2}}{35}b_3$ (error <1%)

The roll motion (cont'd)

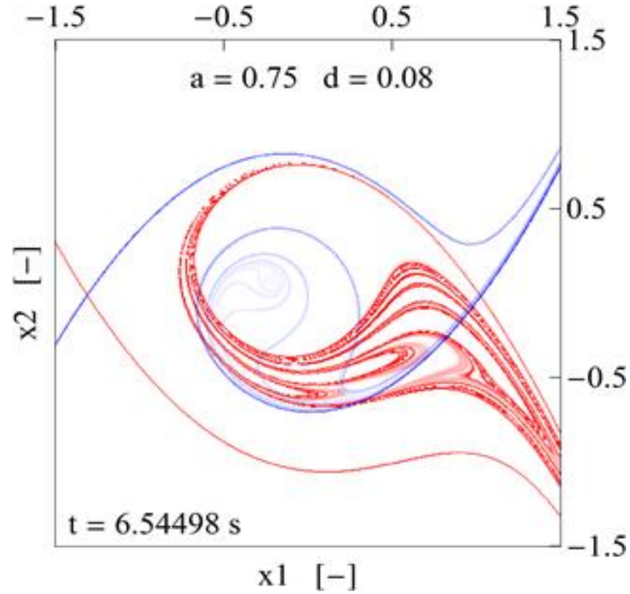
b) With harmonic forcing

Red: inset
Blue: outset

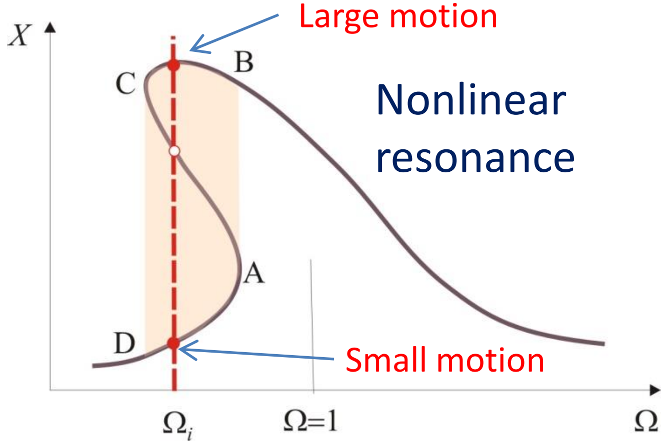
Safe basin split into regions of small and large motion



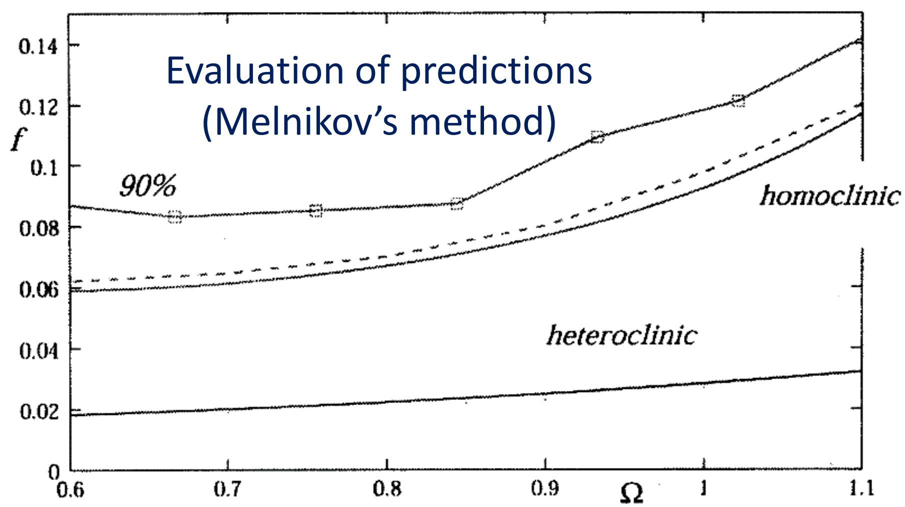
Homoclinic intesections, erosion of large motion's basin



Nonlinear resonance

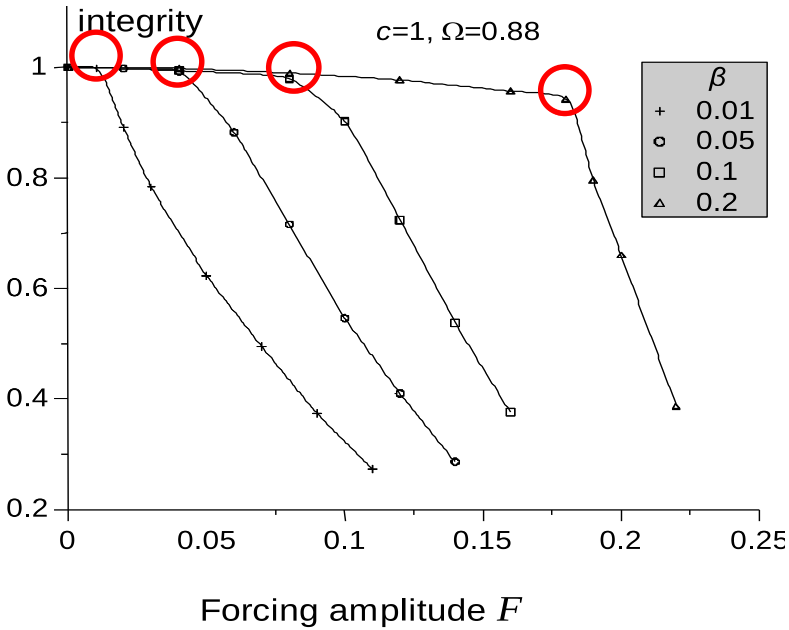


Evaluation of predictions (Melnikov's method)

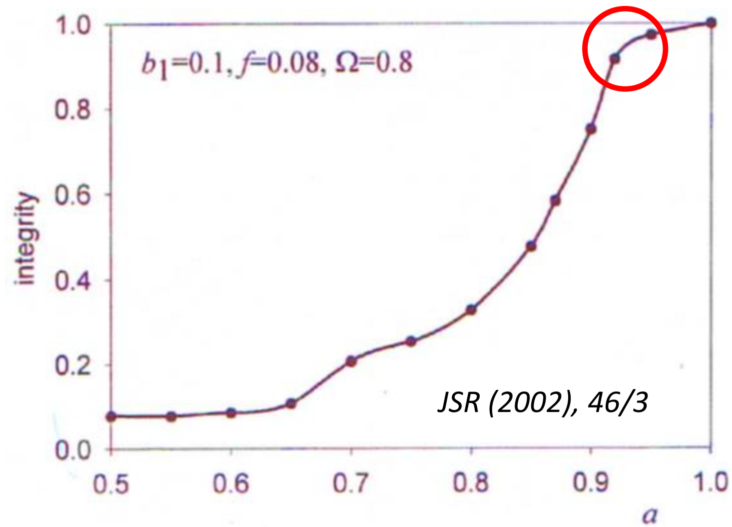


JSR (2002) 46/3

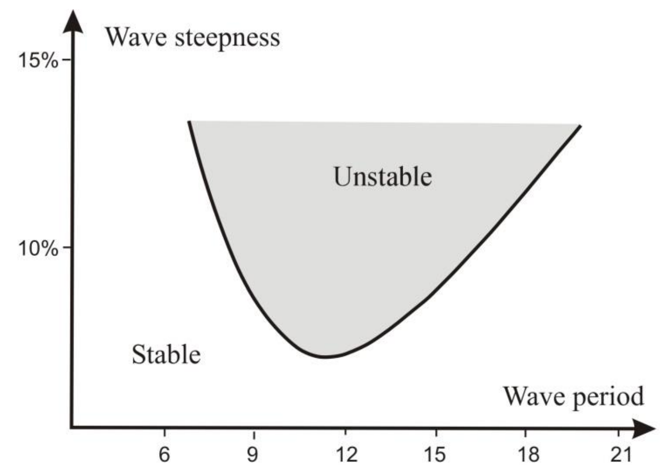
Integrity diagrams (quintic restoring)



Effect of bias (cubic restoring)

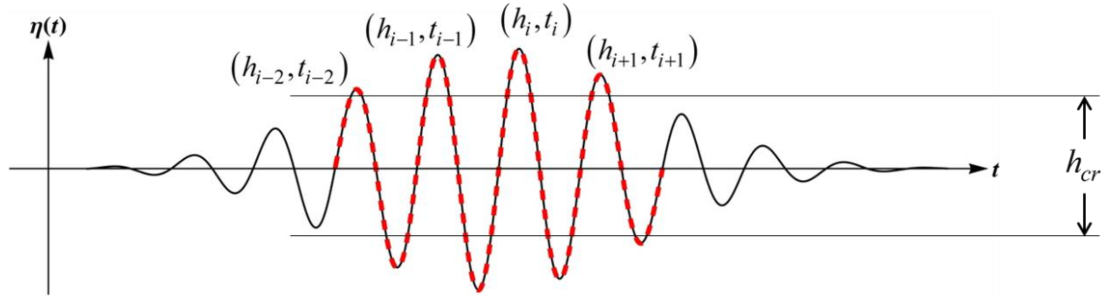


Transient capsize diagram



Stochastic rolling: wave groups

Spectrum-compatible method of wave group construction
Prob. Eng. Mech. 2015; Ocean Eng. 2016)



Markov chain model with cross correlations between heights and periods

Transition probabilities ➡ most expected successions of height and period in group

Karhunen–Loève representation of wave elevation

$$\eta(x,t) = \sum_{n=0}^{\infty} a_n f_n(x,t), \quad -T < t < T$$

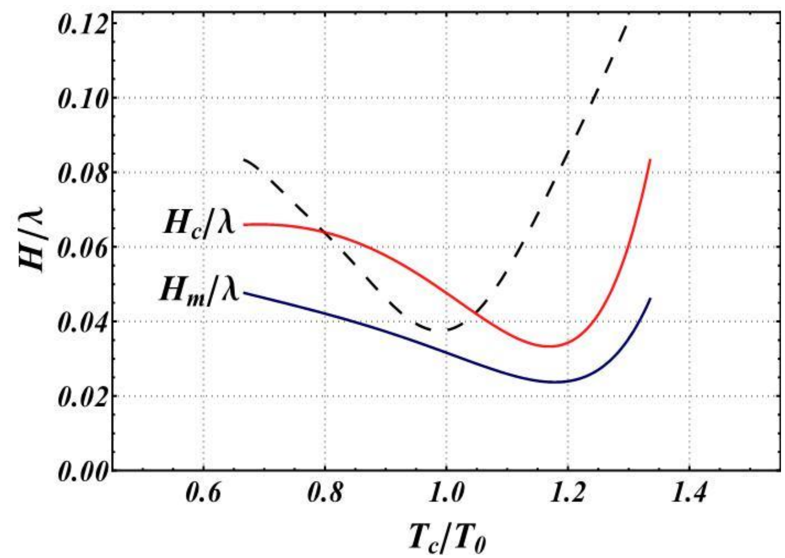
Sclavounos 2012, Proc. R. Soc. Lond. A468

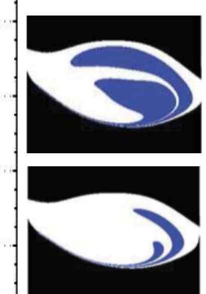
Stability assessment in two parts:

Stochastic modelling
high probability realistic wave group profiles

Ship motion simulations
using derived waveforms

Transient capsize diagram for regular and for realistic wave groups





The following/quartering sea

The broaching-to instability

- ✓ Uncontrolled, rapid deviation from desired course, sometimes ending with capsize

A topic with long history: reports date to 1699

(2010) Trans. RINA 152

“The shipwreck”

Pollock (1810)

(© National Maritime Museum, Greenwich)

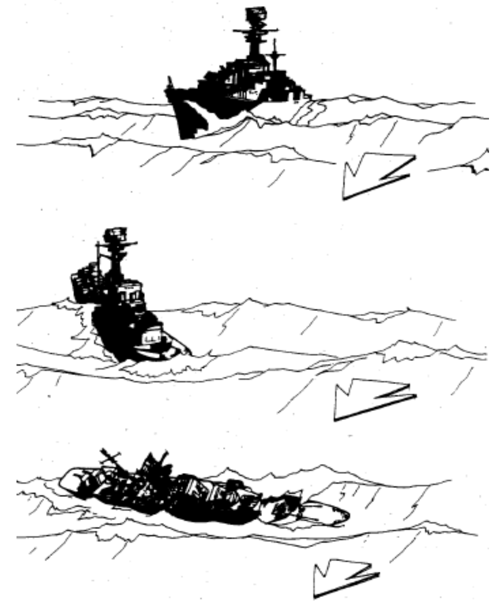
inspired from Falconer (1762)

Distinctive mechanisms *JSR 1995, 40/3*

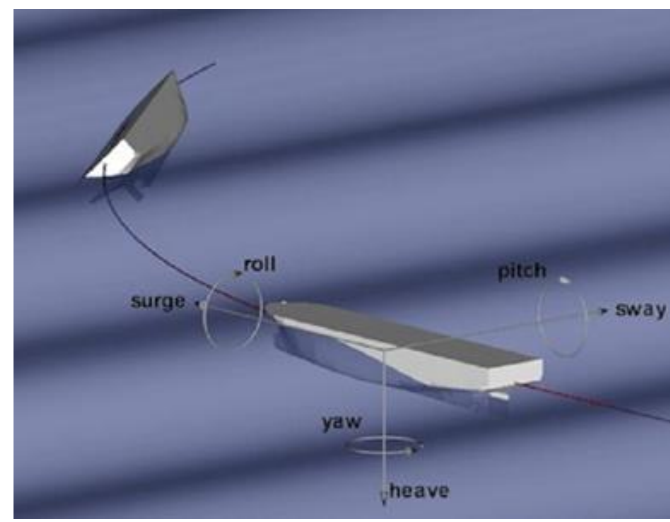
- **via surf-riding** *more common*
- resonant yaw (“direct broaching-to”)

Early scientific investigations:

Davidson (1948); Weinblum & StDenis (1950); DuCane & Goodrich (1962); Grim (1963), Wahab & Swan (1964); Boese (1970); Eda 1972; Motora et al (1982)

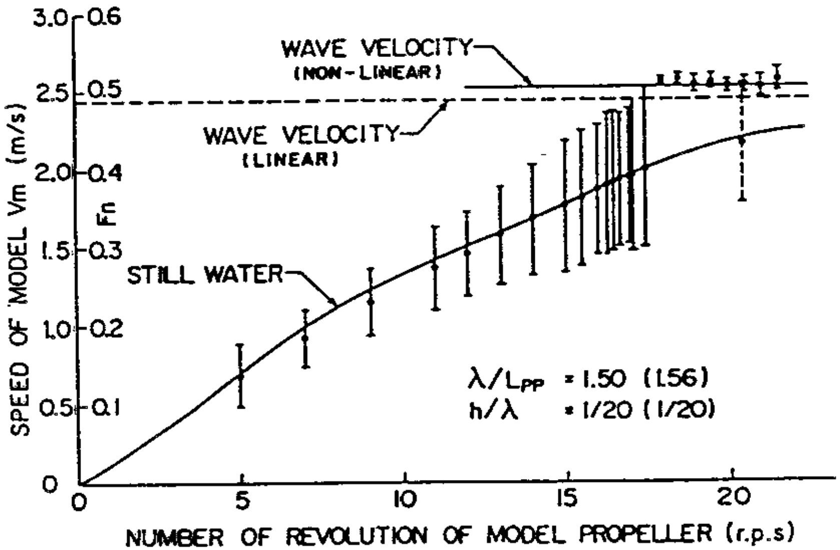


Conolly (1972) J. Mech. Eng. Sci., 14/7

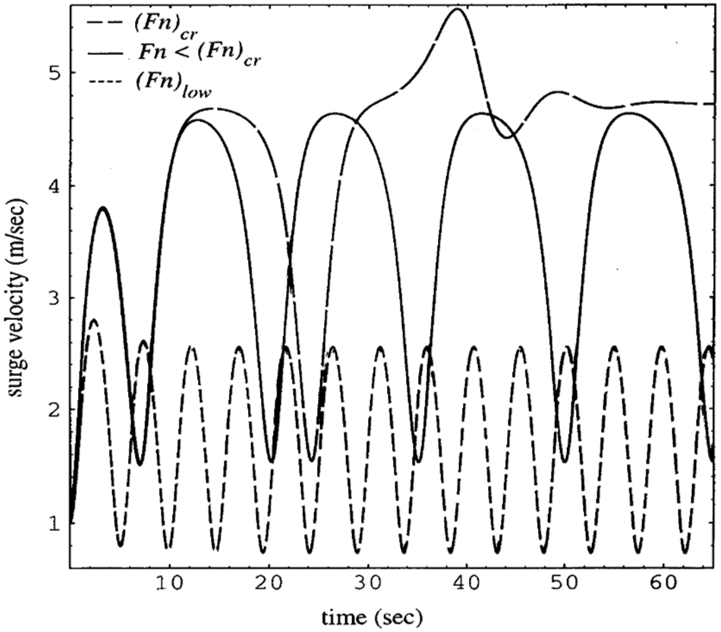


How surf-riding behavior comes about?

Evidence from experiments



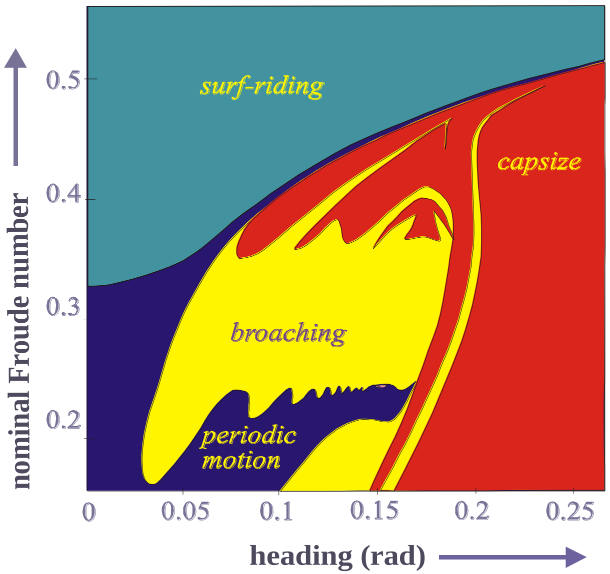
Kan (1990), NAOE, 28, JSNA



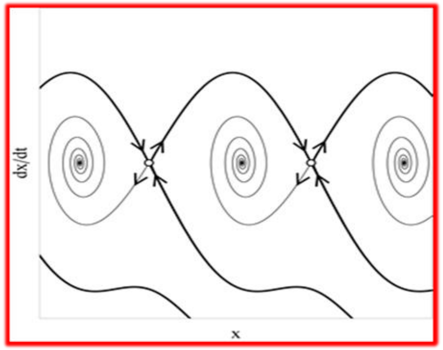
(1996) JSR 40/1

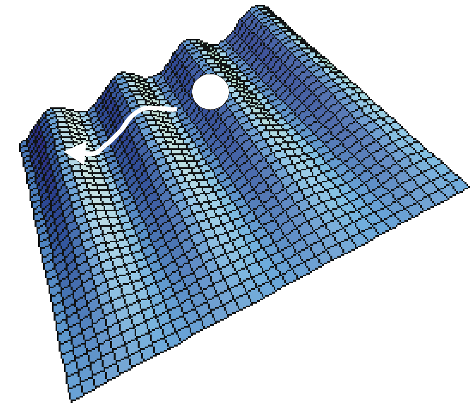
Fn=0.30
Fn=0.35
Fn=0.36

Outcome of effort to escape from surf-riding by reducing speed or by changing heading

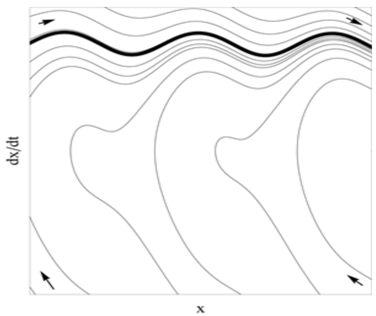


Simple analogues of surf-riding

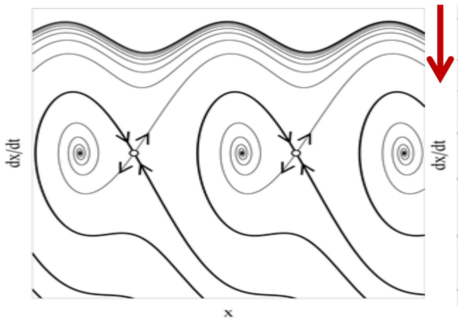




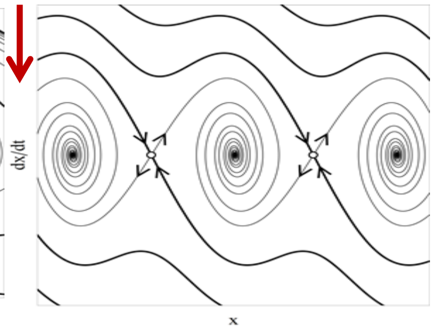
$$U(x) = -\mu \cos x + \alpha x$$



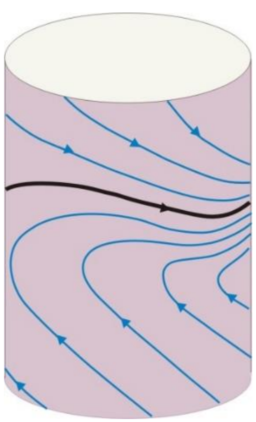
Always downward rolling



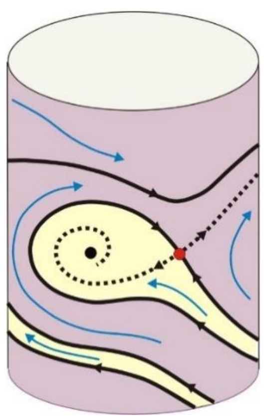
Possible rolling



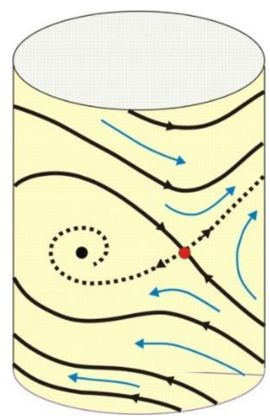
Ball trapped



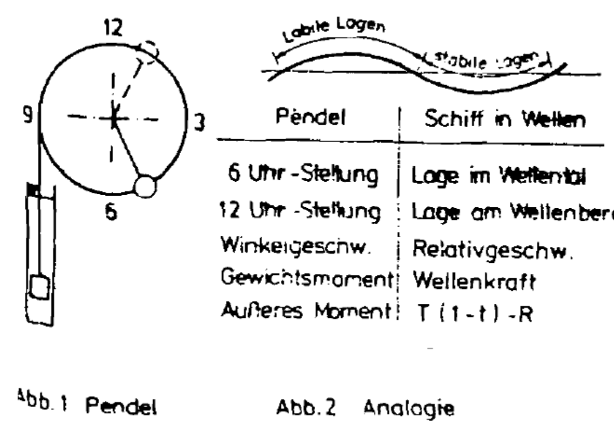
Only rotations



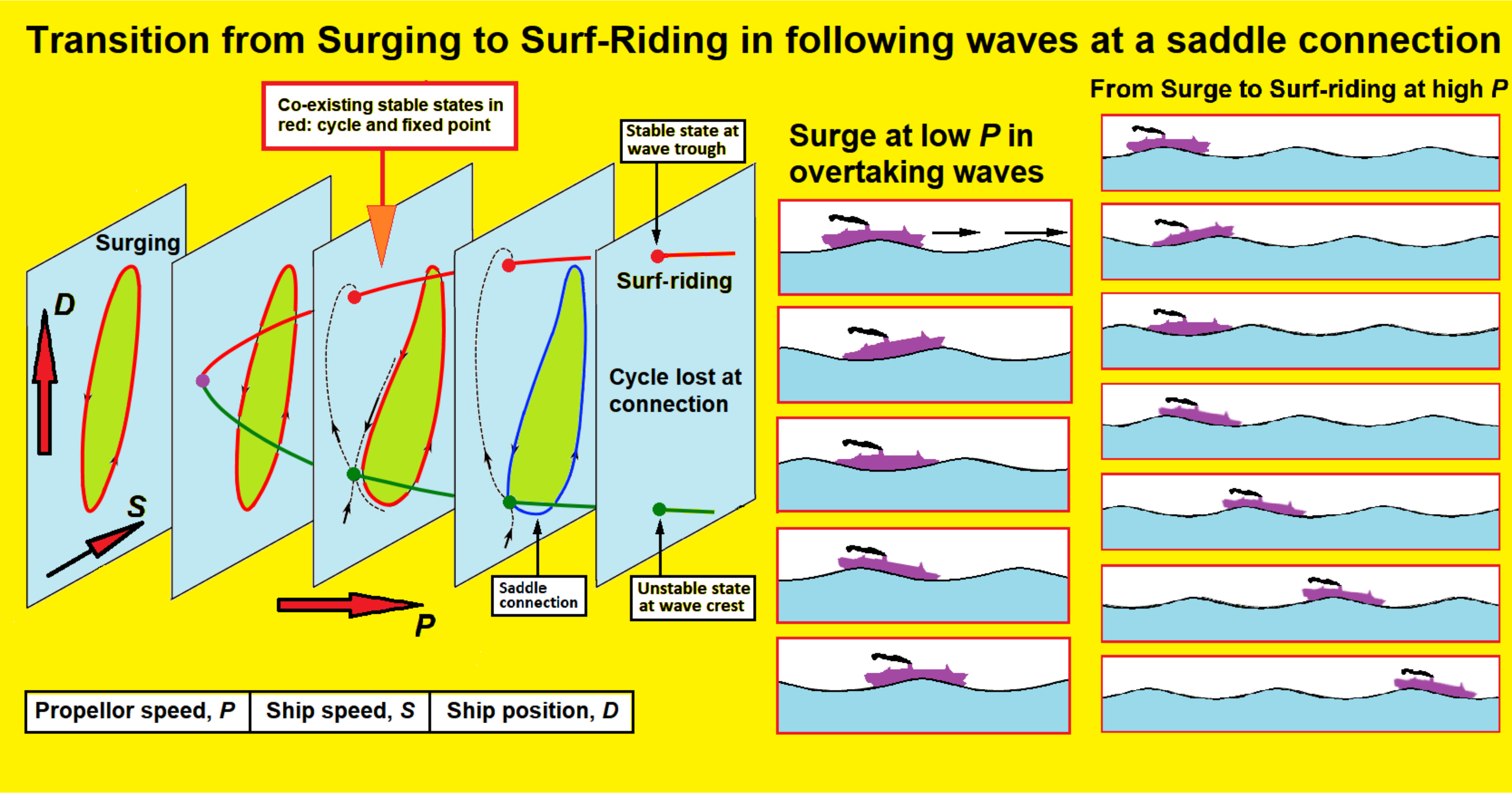
Possible rotations



Fixed location



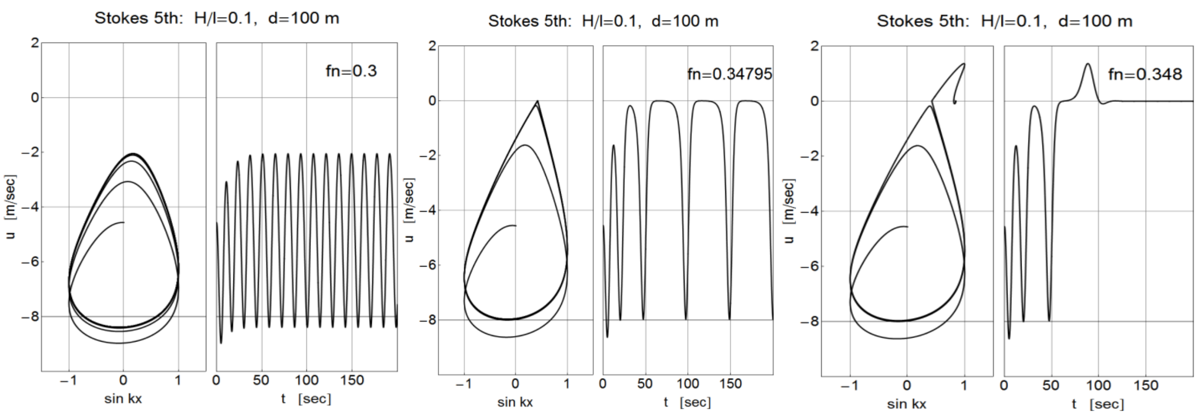
Grim 1983, Schiffstechnik

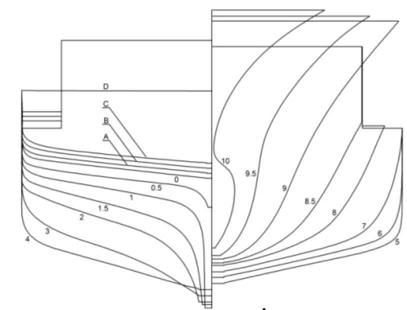


Transition from Surging to Surf-Riding in following waves at a saddle connection
Co-existing stable states in red: cycle and fixed point
Stable state at wave trough
Surging
D
S
P
Surf-riding
Cycle lost at connection
Saddle connection
Unstable state at wave crest
Propellor speed, P
Ship speed, S
Ship position, D
Surge at low P in overtaking waves
From Surge to Surf-riding at high P

Surf-riding in nonlinear waves

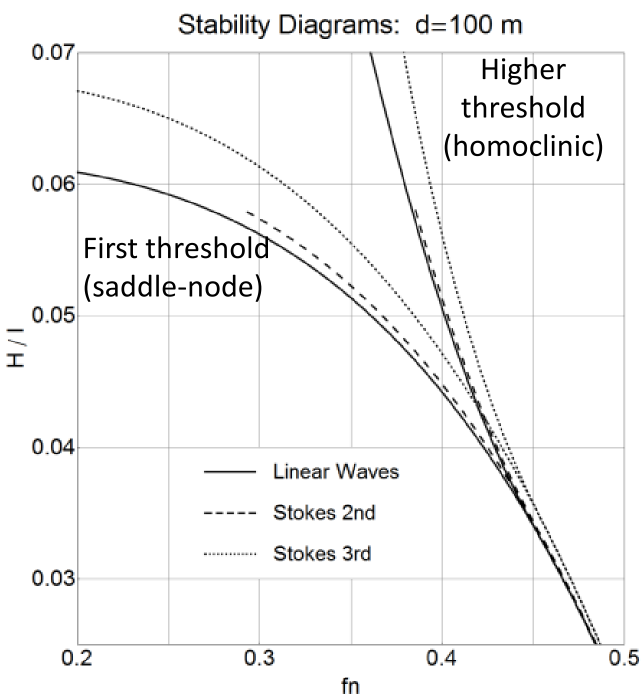
(Fenton's variant of Stokes wave theory)





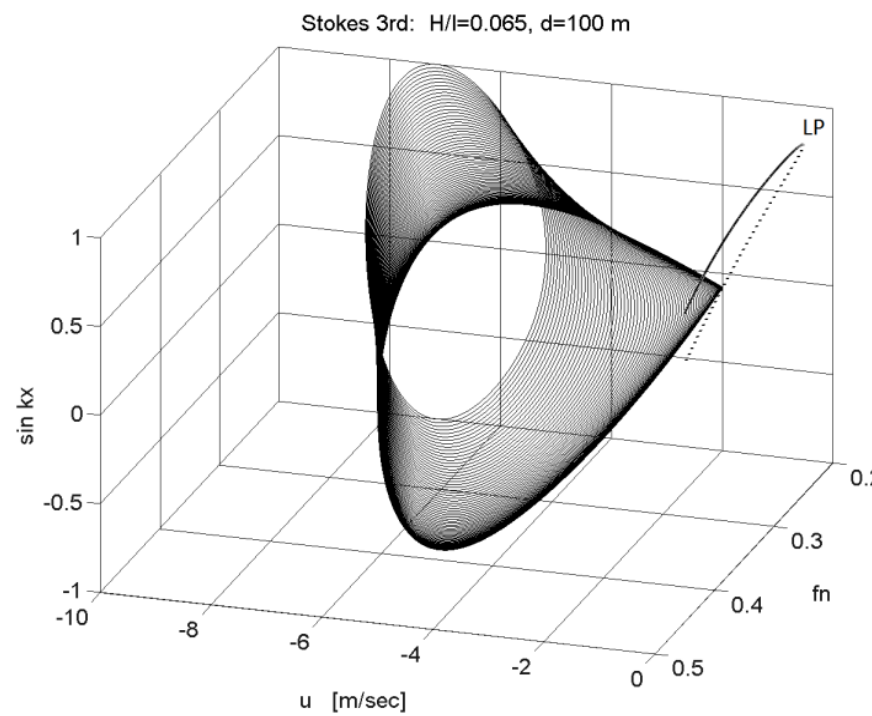
Japanese fishing vessel

Comparison of thresholds : linear versus nonlinear wave



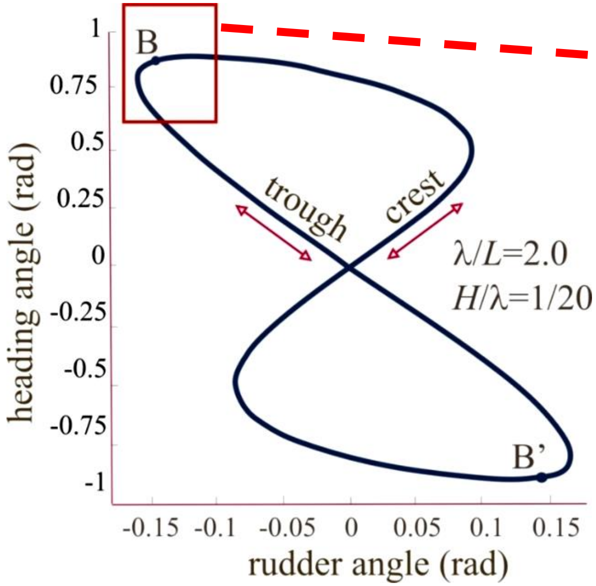
Kontolefas (2013), NTUA Diploma Thesis

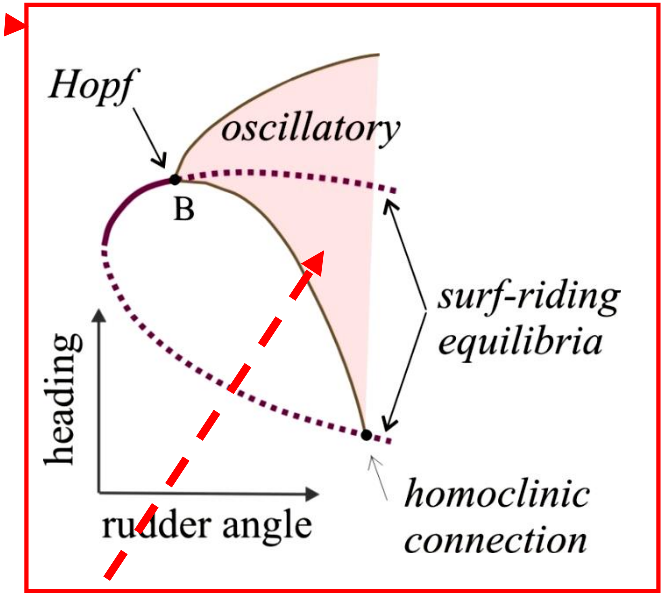
Continuation result: homoclinic saddle connection

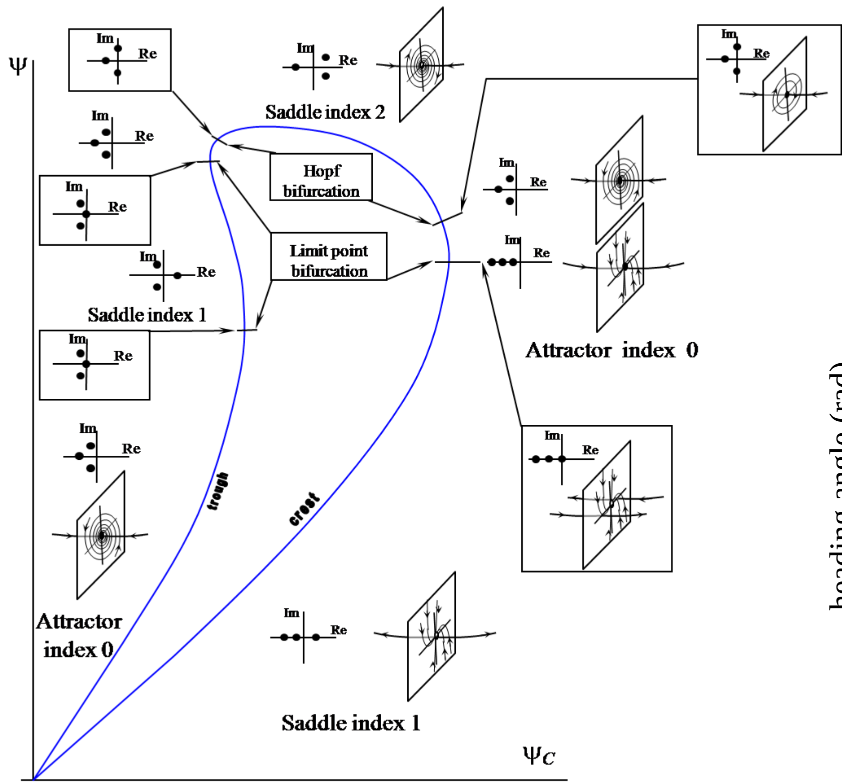


Coupled motions

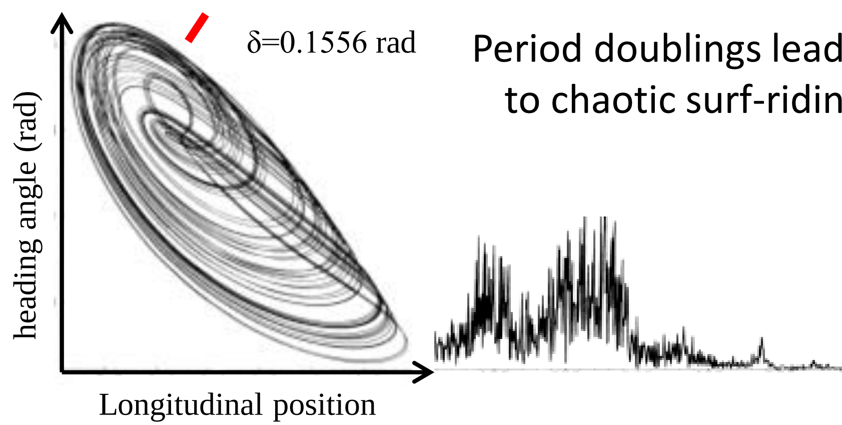
Yaw/sway







(1996) CHAOS, 6/2

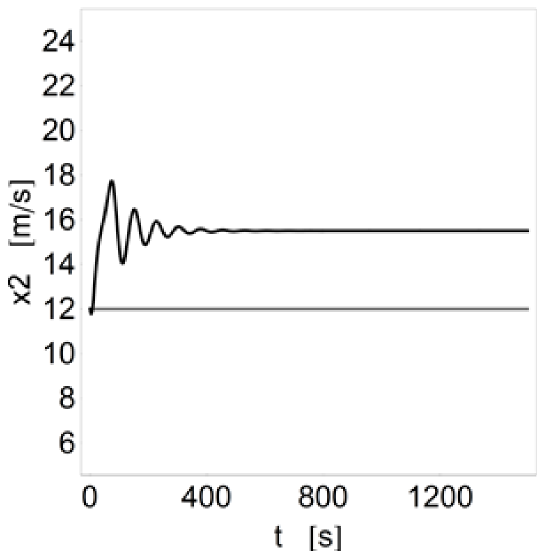


Period doublings leading to chaotic surf-riding

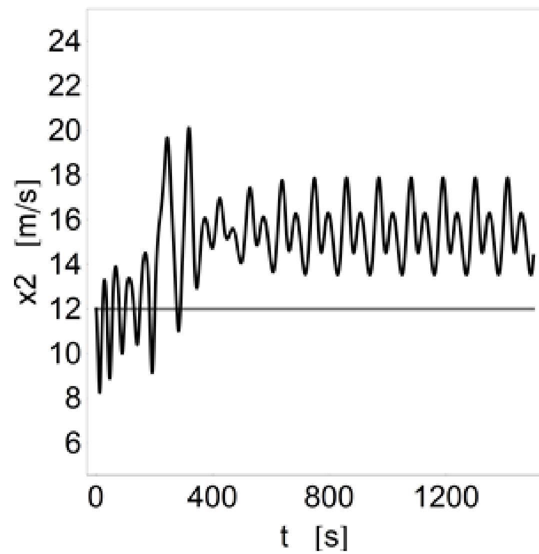
Surging and surf-riding in multi-chromatic seas

Spatiotemporal framework

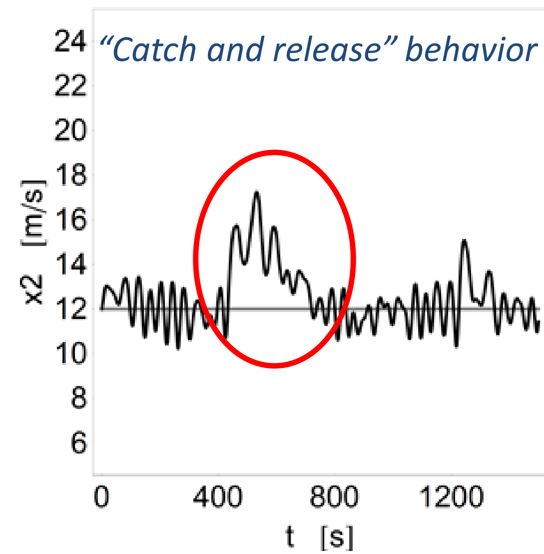
1-frequency excitation



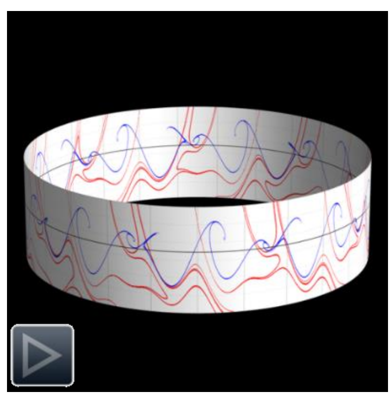
2-frequency excitation

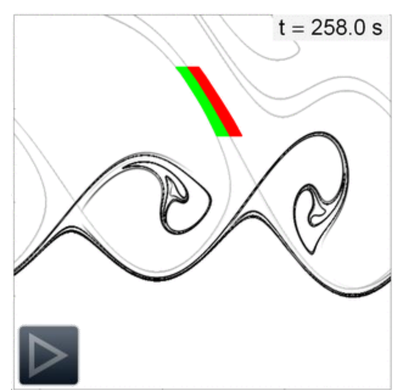


Multi-frequency excitation

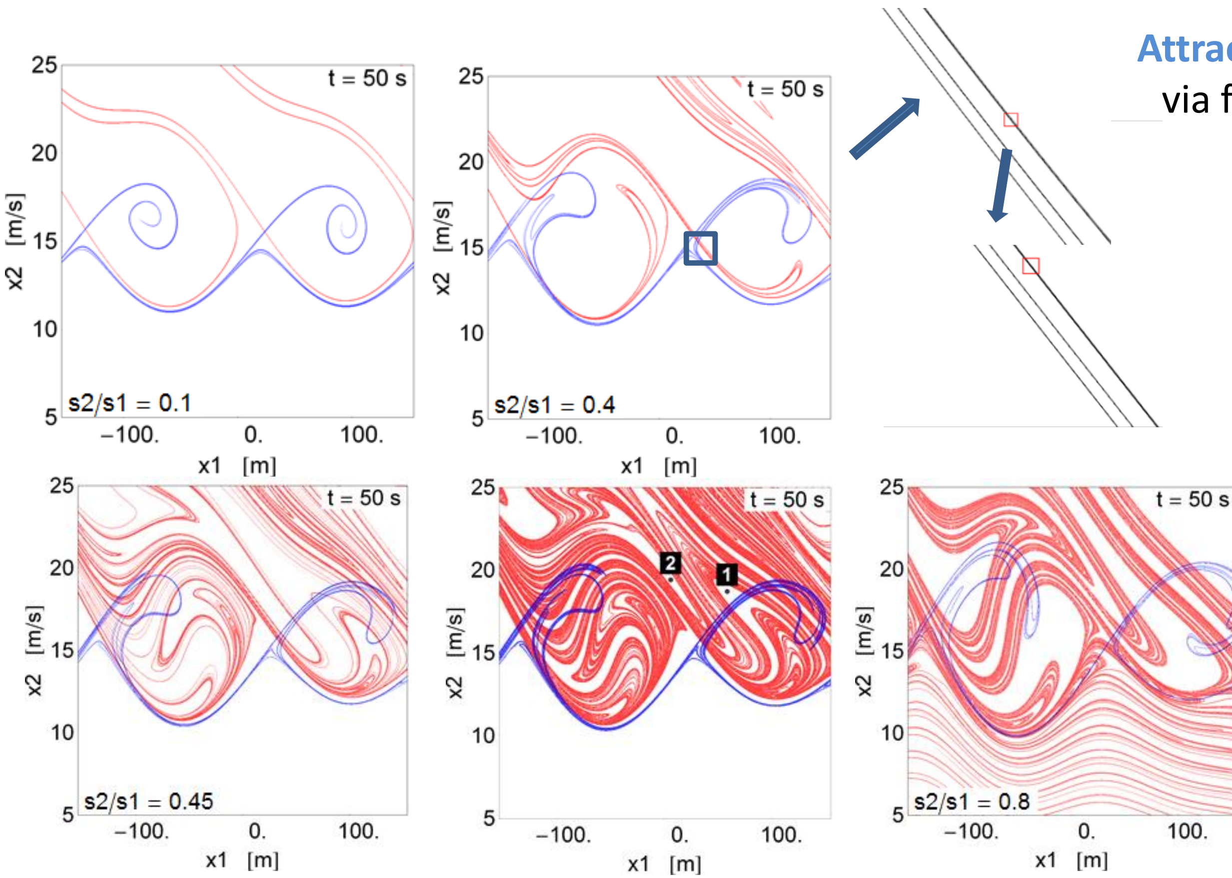


(2016) 31st SNH

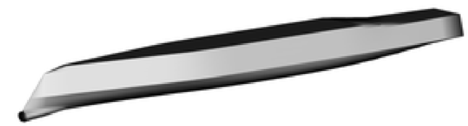




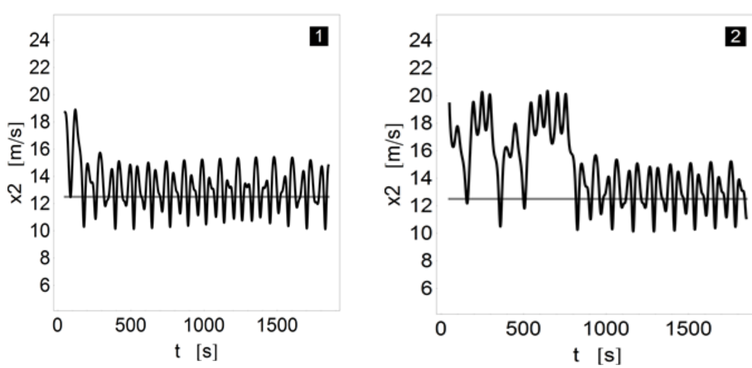
Nonlinear surge motions - bi-chromatic excitation



Attracting (blue) and **repelling (red)** **LCS** via forward and backward **FTLE** fields



L	154 m
B	18.8 m
T	5.5 m
m	8858,38 t
U_S	12 m/s



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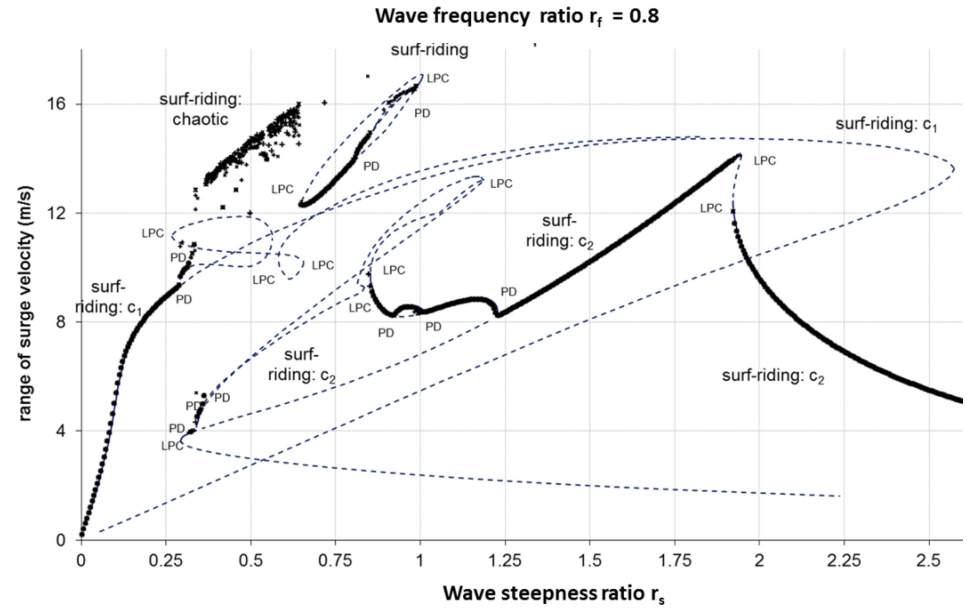
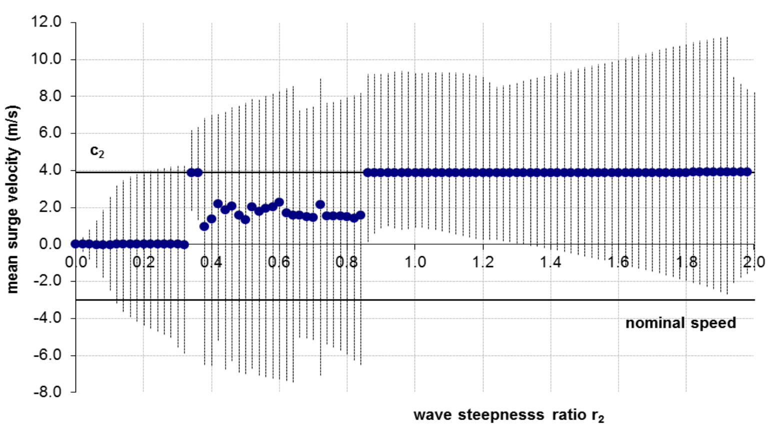
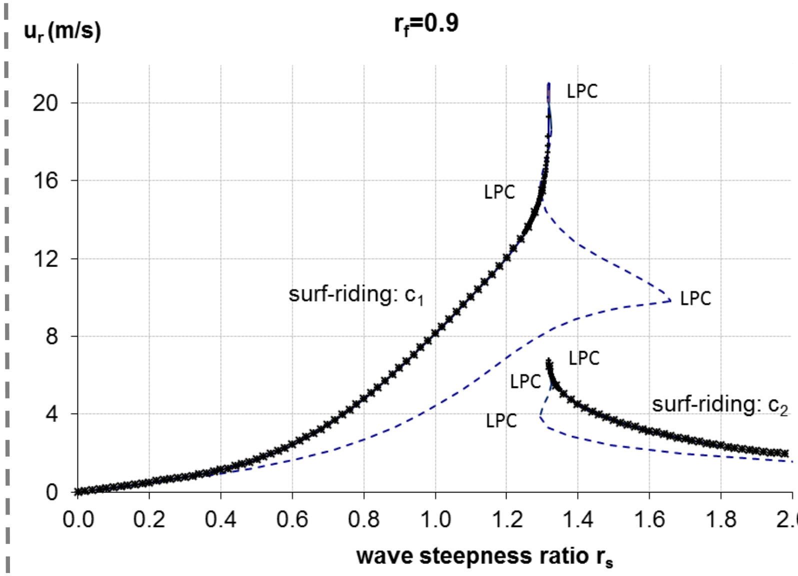
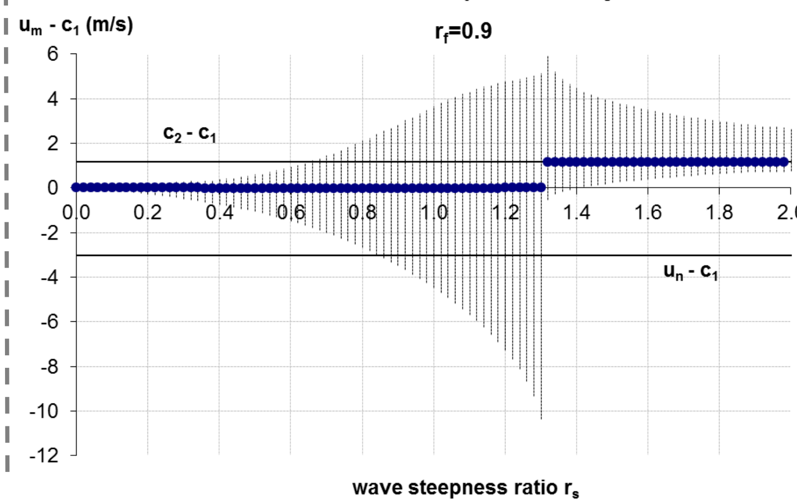
Continuation result: arrangement of steady surf-riding states





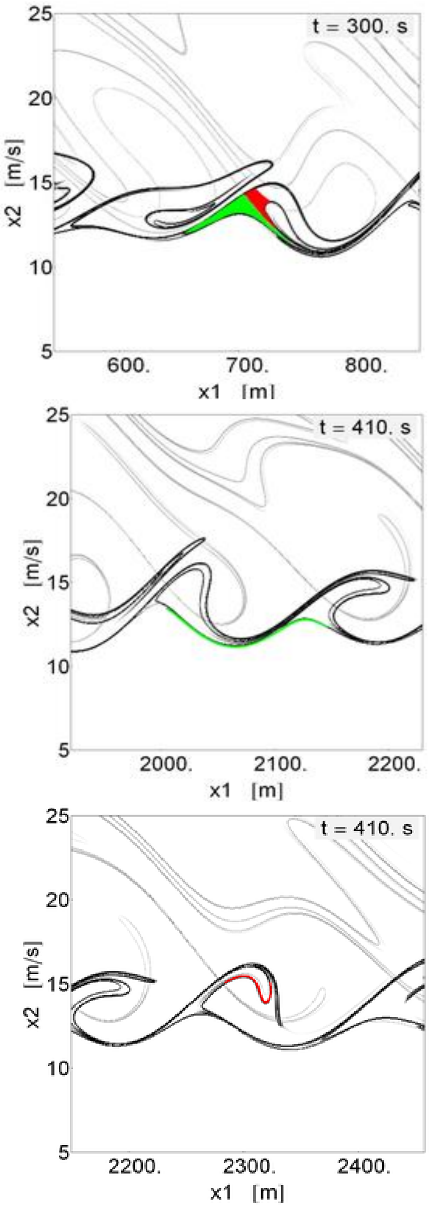
Comparative result from another ship with sharper separation of dynamics



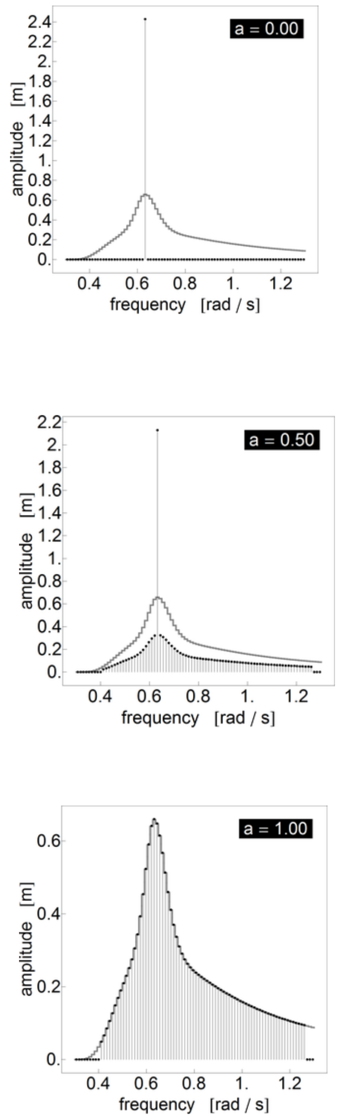


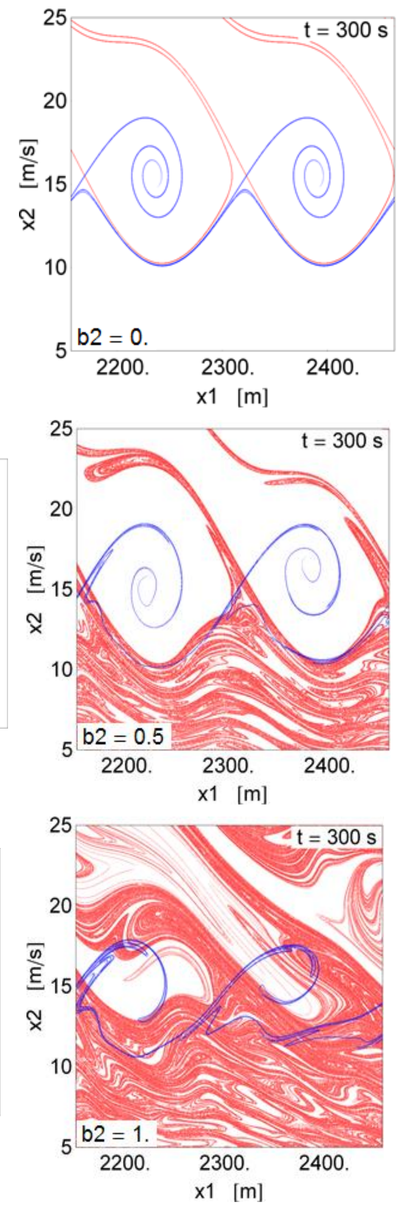
Behavior in irregular seas

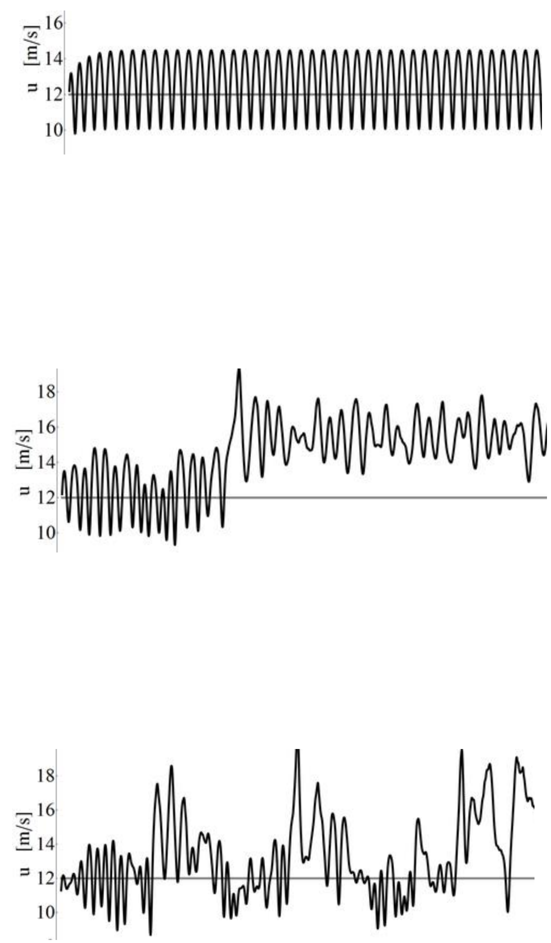
Attracting (black) and repelling (grey) LCS - - JONSWAP spectrum



Converting excitation from regular to irregular







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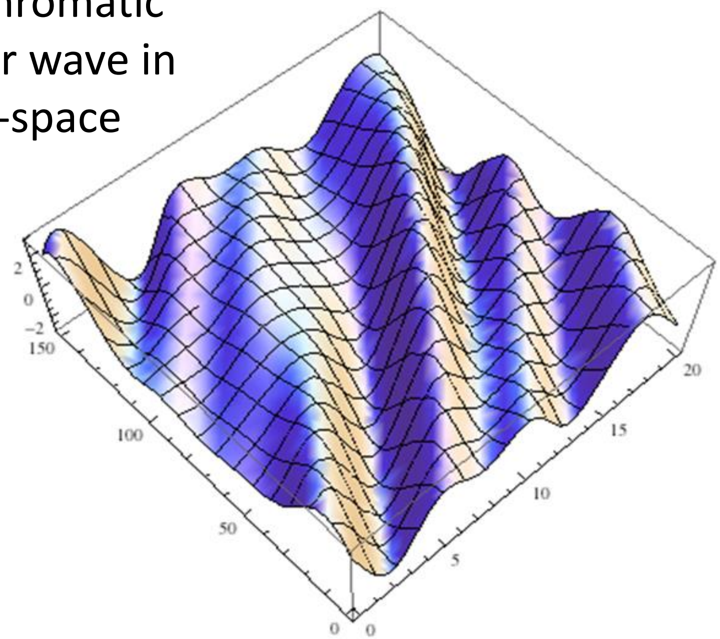
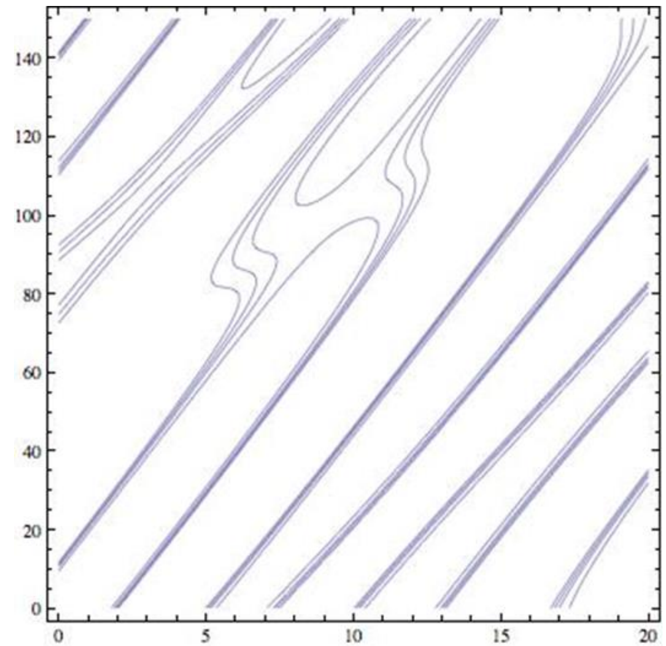
Computation of local celerity

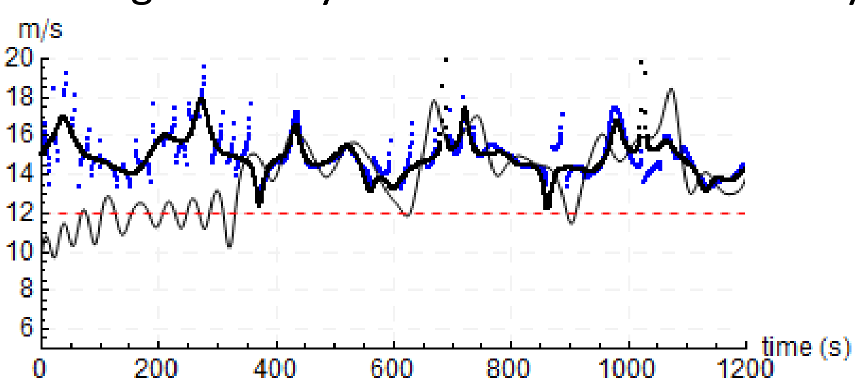
Tri-chromatic linear wave in time-space



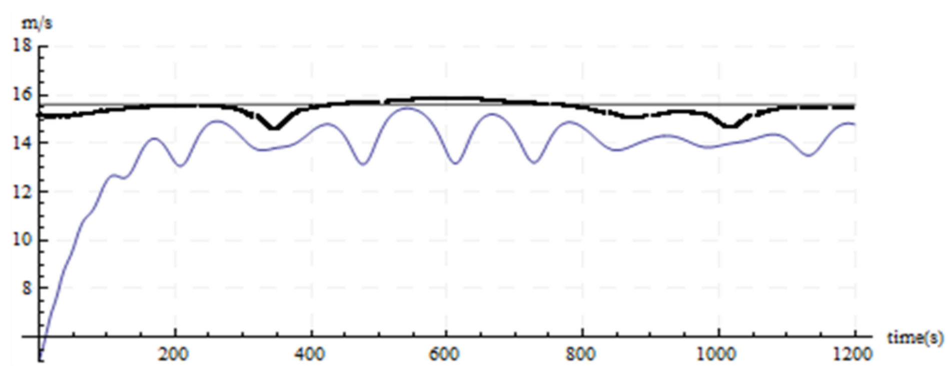
Lines of constant wave slope



Surge velocity and instantaneous celerity



Celerity at nearest wave max slope

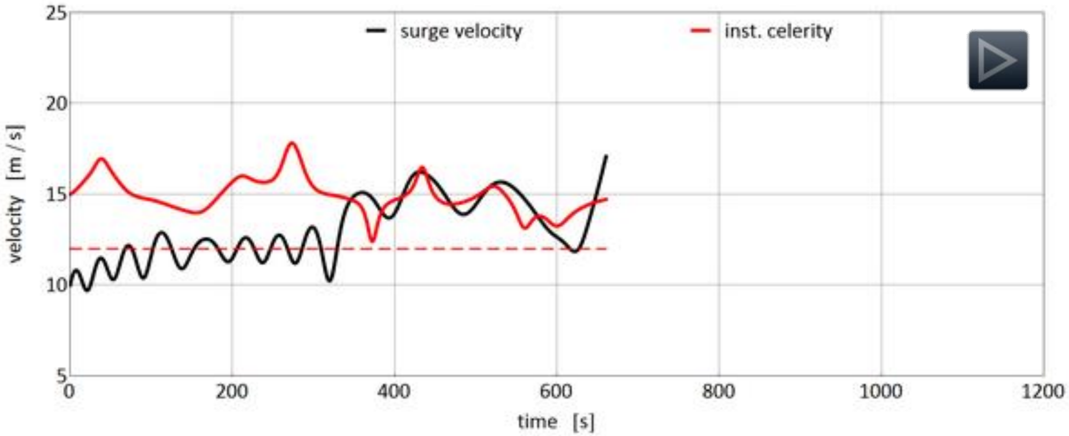


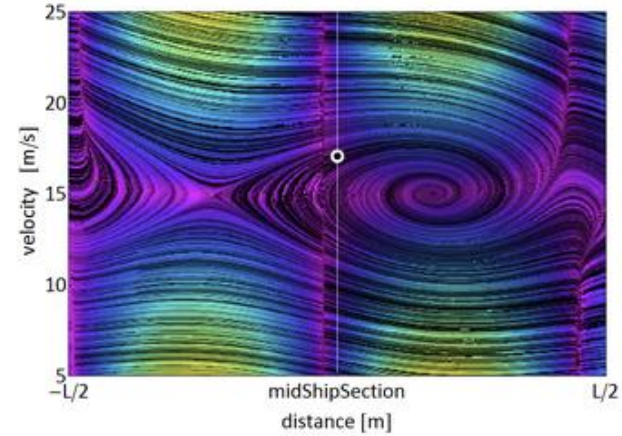
The "feature flow field" method

Theisel & Seidel (2003) VisSym03

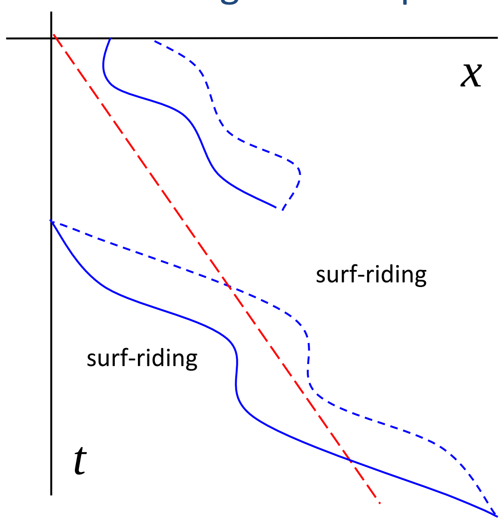
curves of minimal change of velocity in phase-space

$$V\left(x_1, x_2, t\right) = \nabla \dot{x}_1 \times \nabla \dot{x}_2$$

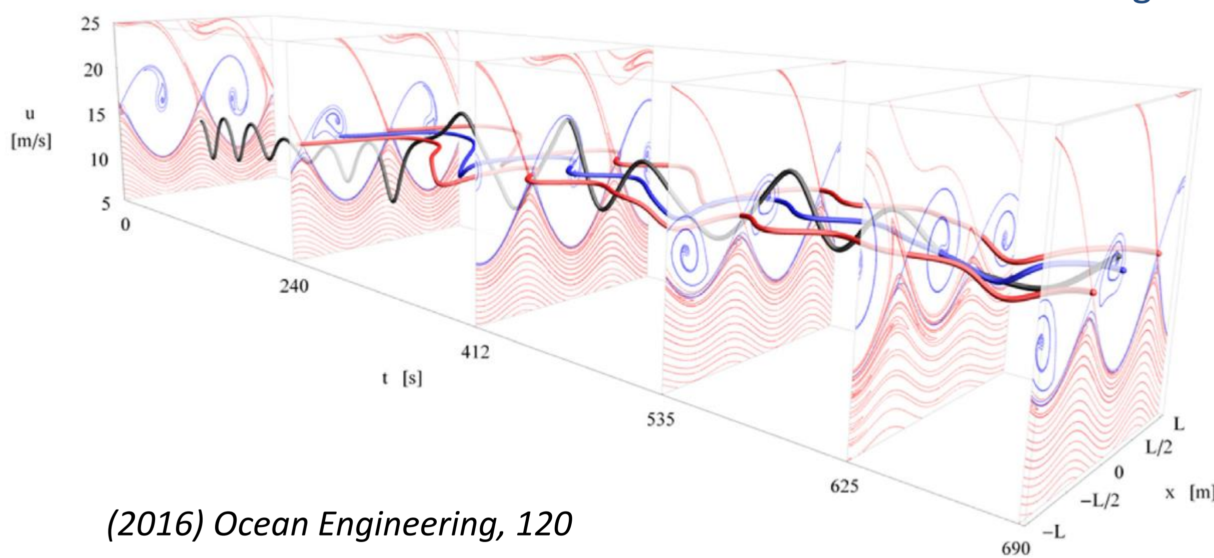




Intermittent intervals of surf-riding in time-space



LCS combined with "feature" tracking



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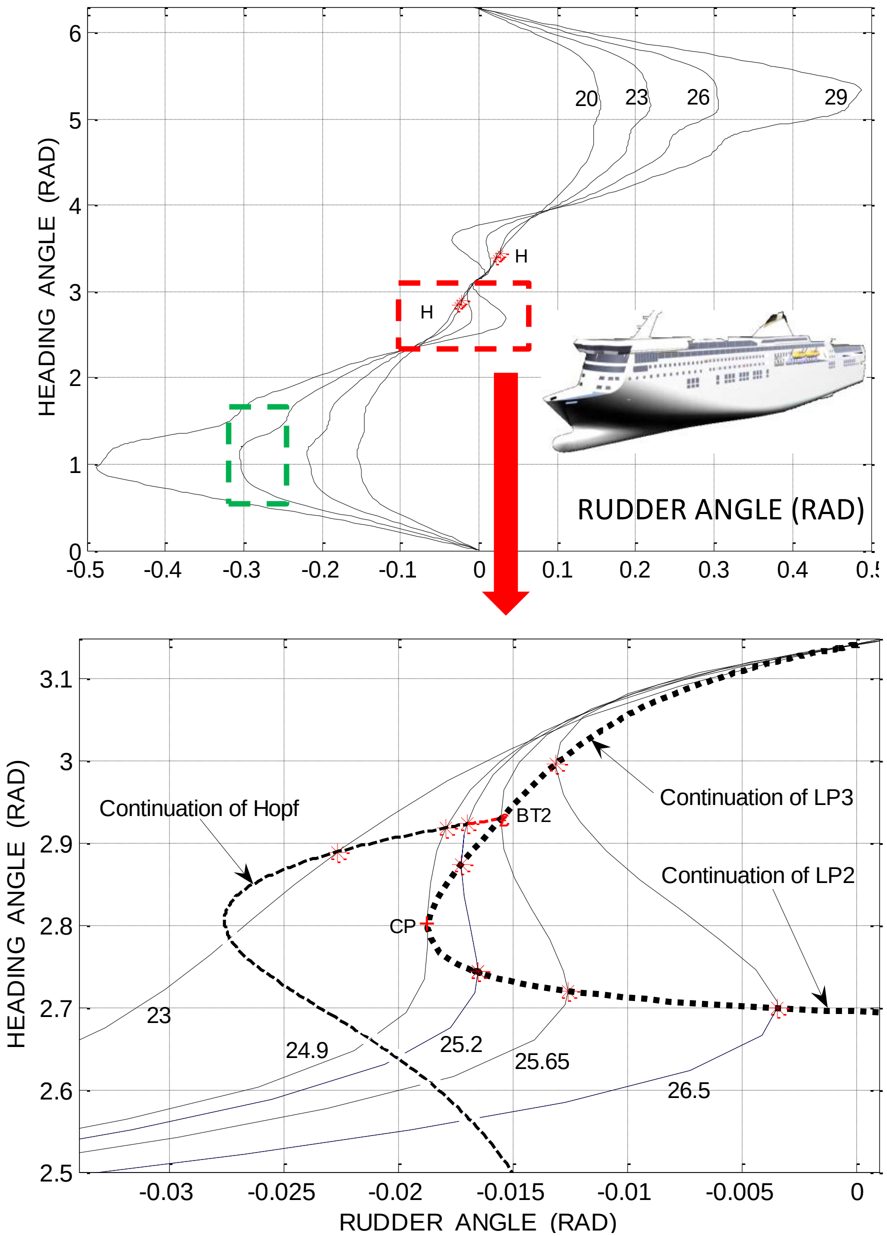
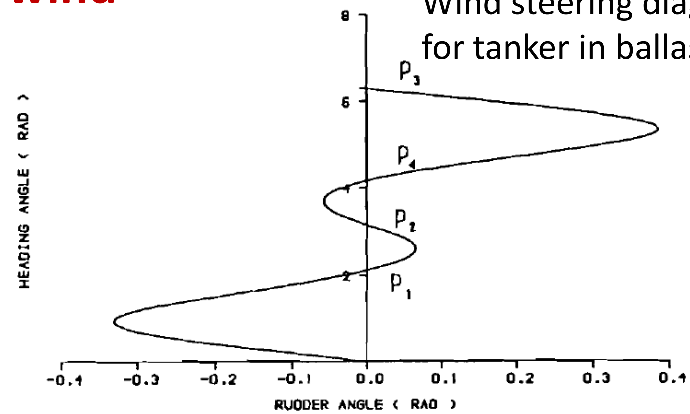
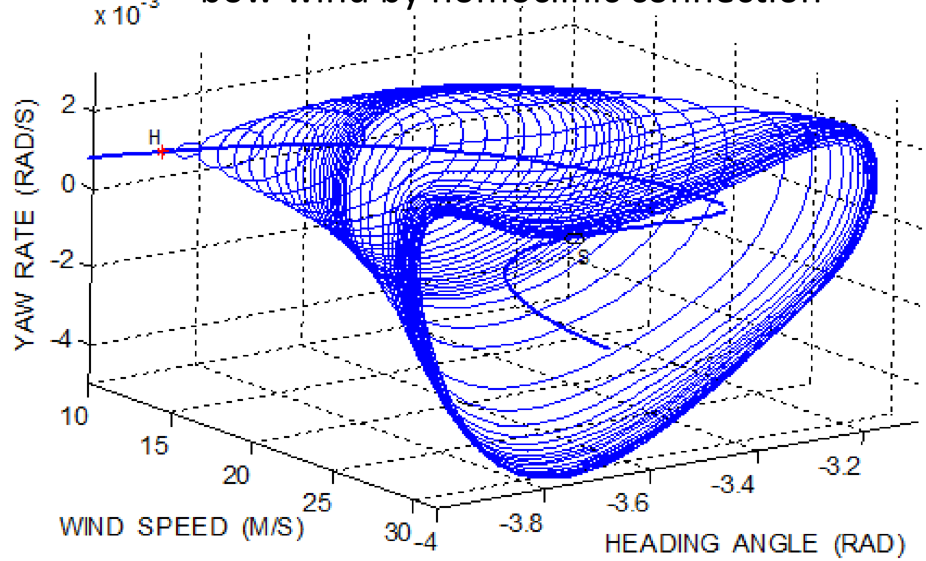
Maneuvering and course-keeping in strong wind



Wind steering diagram for tanker in ballast

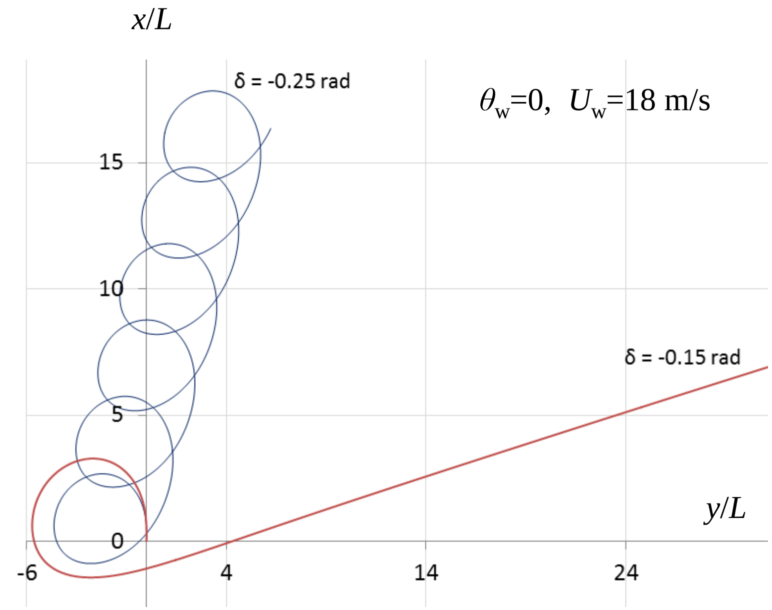


End of self-sustained oscillations in bow wind by homoclinic connection

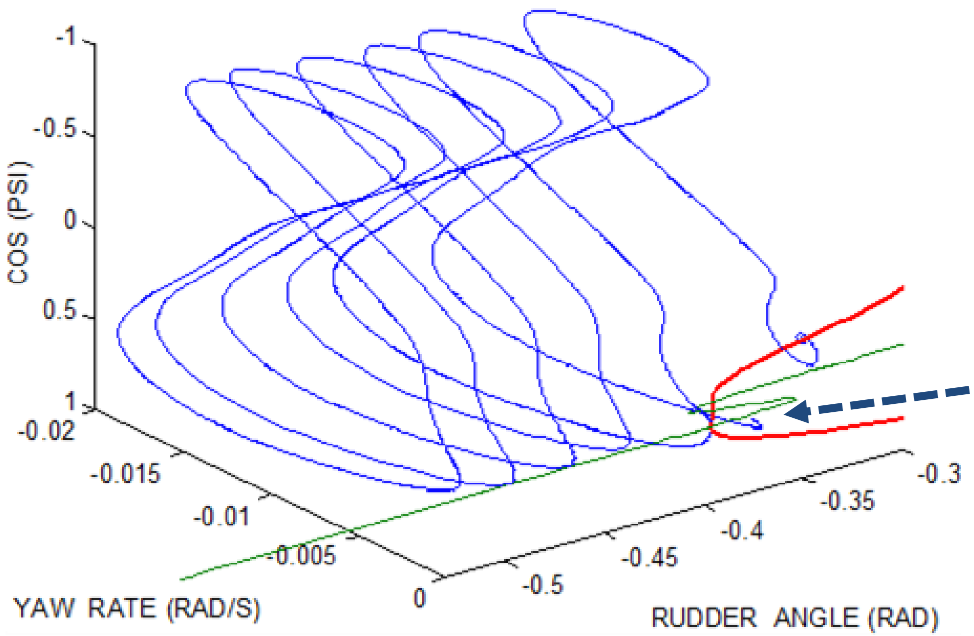


Scenario with sluggish rudder control

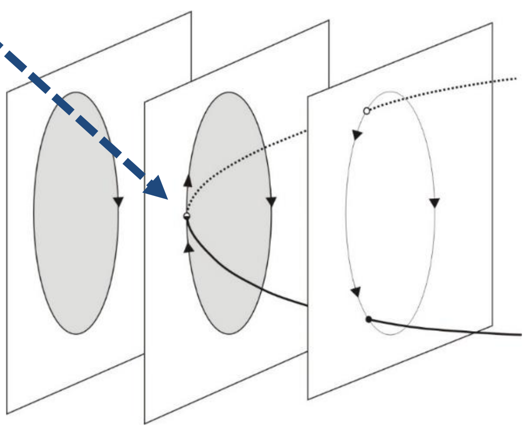
Maneuvering and course-keeping in strong wind (cont'd)



Competing turning and straight-line motion



Homoclinic to saddle-node



Final remarks

- ✓ Homoclinic phenomena are quite widespread in ship motions.
- ✓ Their investigation in multi-chromatic seas is the state-of-art topic, enabled by recent advances in computational techniques.
- ✓ Efforts to incorporate more detailed mathematical models should be strengthened.
- ✓ Excellent prospect for developing rigorous probabilistic assessments of ship stability-related problems.
- ✓ Efficiency issues exist due to combination of complex physics with rarity.
- ✓ Need to include relevant courses in naval architecture curricula.