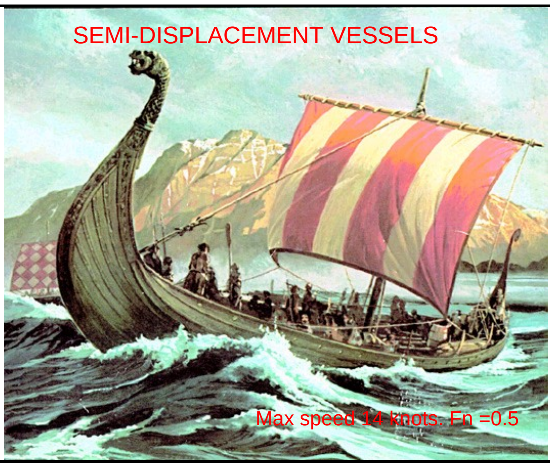
Semi-displacement vessels lecture 1

O.M.Faltinsen

Content

- Resistance
- Wave resistance and wash
- Wave-induced motions
- Added resistance in waves
- Dynamic stability
- Maneuvering



SWATH

Wave-piercing catamaran

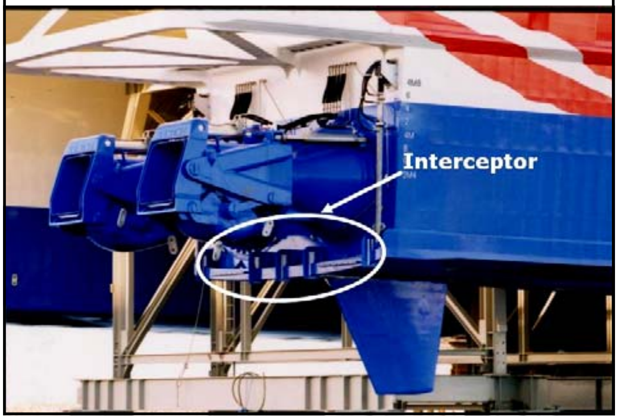
Trimaran

Pentamaran

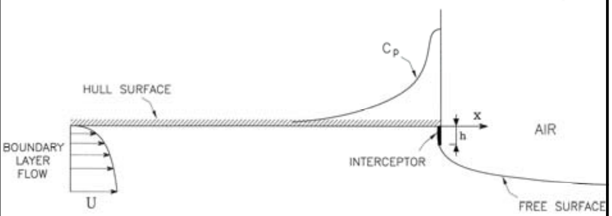
T-foil

Trim tab installation

Interceptor and high-speed rudder



Flow and pressure due to interceptor

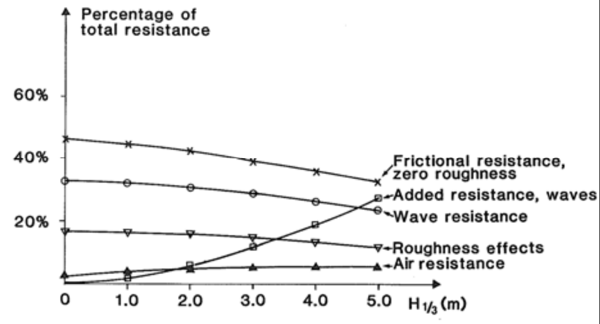


Antiroll damping fin

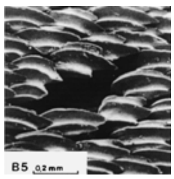
Resistance

- Spray resistance
- Air resistance
- Viscous resistance
  - Form factors (Molland et al)
  - Flow separation at transom stern
- Wave resistance
- Wash
  - Wave decay of wave systems

Resistance components for 70m catamaran

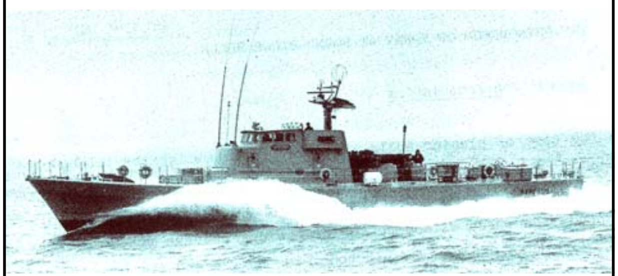


What can we learn about resistance and propulsion of aquatic animals?

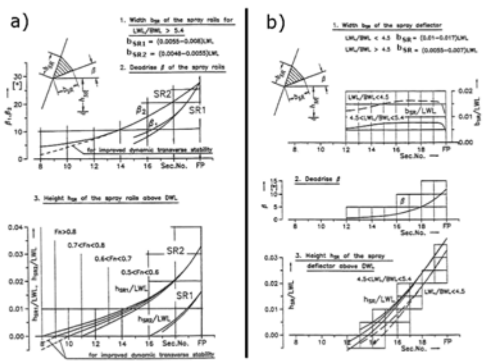


White shark skin

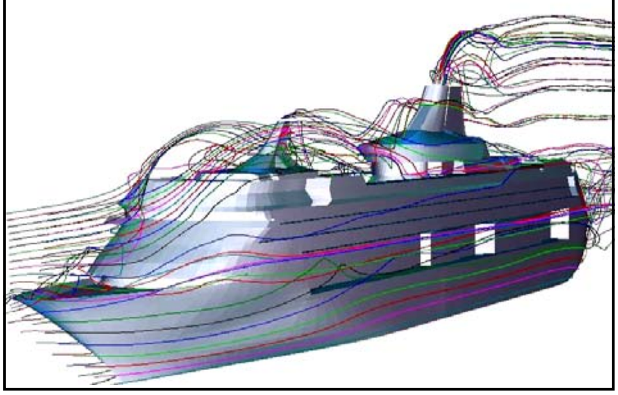
Spray resistance



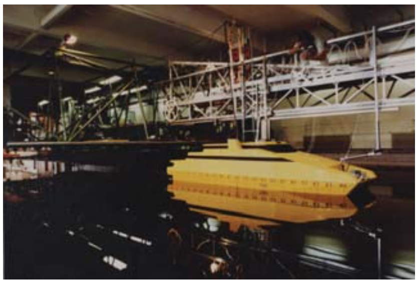
Spray rails and deflectors (Muller-Graf)



Air resistance and flow



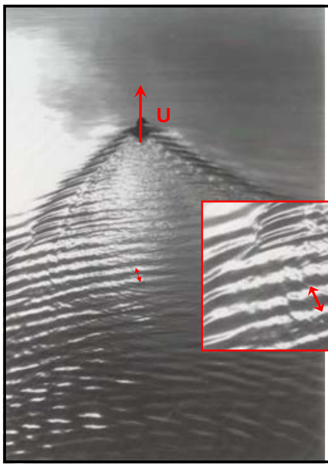
Measurement of air resistance



Bias due to towing carriage

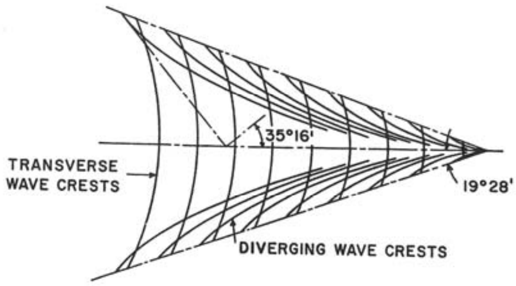
$Rn_{air} \approx 0.1 Rn_{water}$

Wave resistance and wash

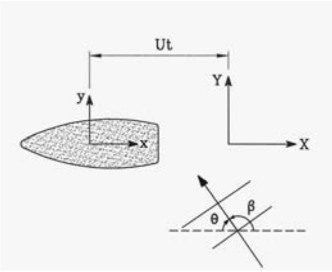


Kelvin waves by a duck

Divergent and transverse steady waves in deep water



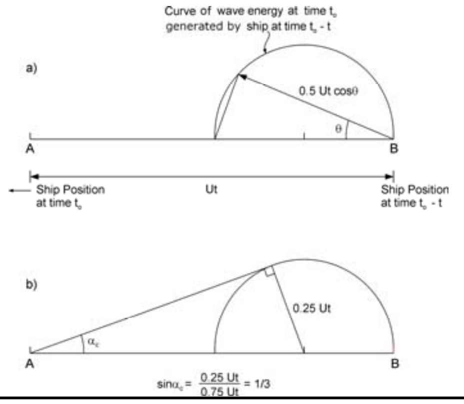
Wave length and group velocity in deep water



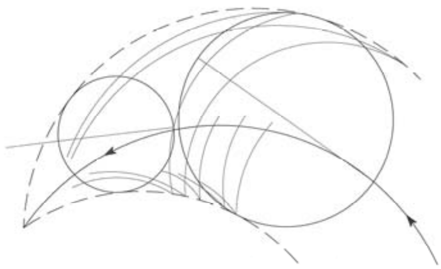
$$\lambda = \frac{2\pi}{g} U^2 \cos^2 \theta$$

$$V_g = \frac{1}{2} U \cos \theta$$

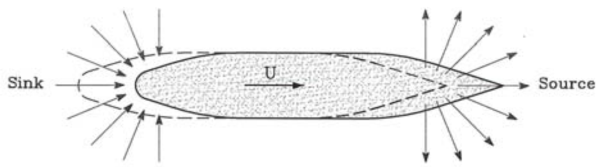
Kelvin angle in deep water

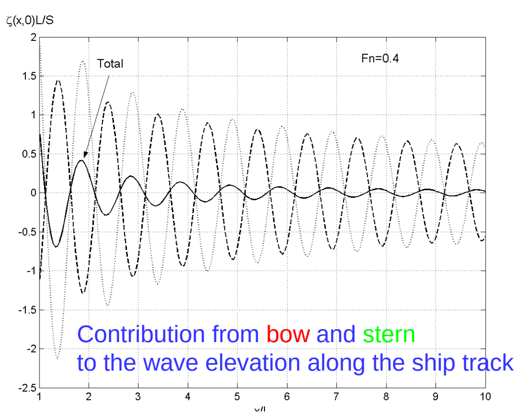


Kelvin angles during turning



The ship moves the water





Contribution from bow and stern
to the wave elevation along the ship track

Wave resistance by Michell's theory

$$R_W = 0.5\pi\rho U^2 \int_{-\pi/2}^{\pi/2} \left|A(\theta)\right|^2 \cos^3 \theta d\theta$$

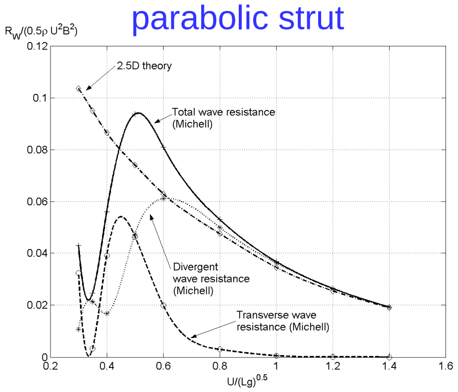
$$A(\theta) = \frac{2}{\pi} \nu \sec^3 \theta \iint_{cp} \frac{\partial \eta}{\partial x} \exp\left[\nu \sec^2 \theta \left(z + ix\cos\theta\right)\right] dzdx$$

$$\nu = g / U^2, \sec\theta = 1/\cos\theta, cp = centerplane$$

Transverse waves: $0 \le |\theta| \le \sin^{-1}\left(1/\sqrt{3}\right)$

Divergent waves: $\sin^{-1}\left(1/\sqrt{3}\right) \le |\theta| \le \pi/2$

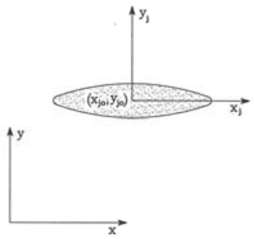
Wave resistance of Tuck's parabolic strut



Wave resistance of multihull vessel

Wave amplitude function by linear superposition

$$A(\theta)=\sum_{j=1}^{N} A_j(\theta)\exp\left[-i\frac{g}{U^2\cos^2\theta}(x_{jo}\cos\theta+y_{jo}\sin\theta)\right]$$



Wave resistance of catamaran with nonstaggered identical demihulls

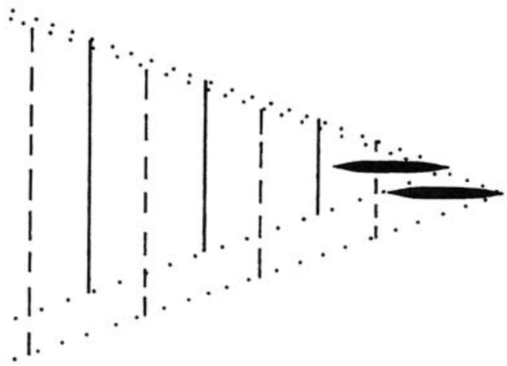
$$R_W=\frac{\pi}{2}\rho U^2\int_{-\pi/2}^{\pi/2}\left|A(\theta)\right|^2_{SH}4\cos^2\left(\frac{p/L}{Fn^2\cos^2\theta}\sin\theta\right)\cos^3\theta\, d\theta$$

SH=Side hull

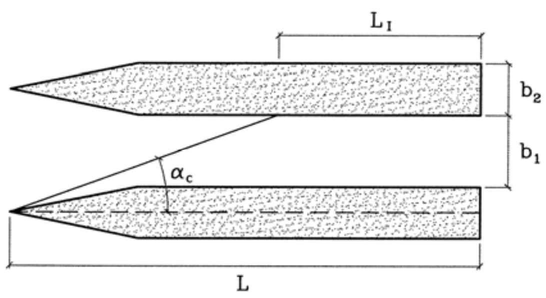
2p=Centerlines distance

L=Ship length

Transverse wave crests generated by two staggered hulls (Søding)



Hull interaction due to wave effects



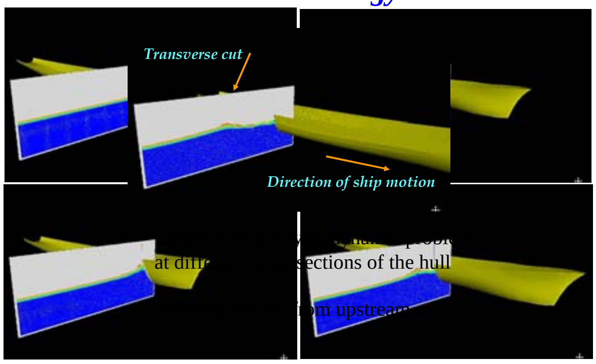
Nonlinear wave generation

Criterion for flow separation from the transom stern

$$\frac{U}{(gD)^{1/2}} > 2.5$$

D=Draft at the transom

Numerical Simulation: 2D+t Strategy



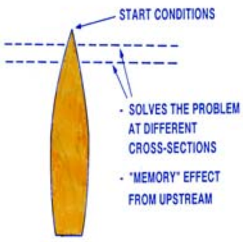
2.5D (2D+t) theory with potential flow theory

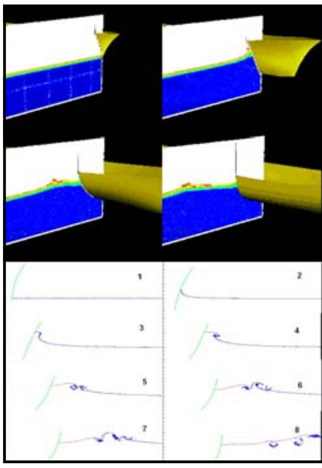
Solution procedure

$$\frac{\partial \zeta}{\partial x} = -\frac{1}{U}\frac{\partial \varphi}{\partial z} - \frac{1}{U}\frac{\partial \varphi}{\partial y}\frac{\partial \zeta}{\partial x}, z = \zeta(x, y)$$

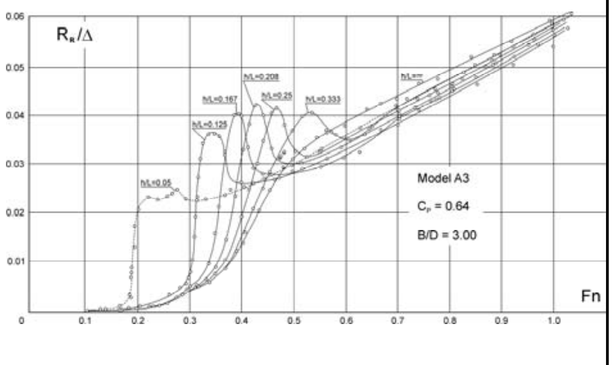
$$\frac{\partial \varphi}{\partial x} = -\frac{g}{U}\zeta - \frac{1}{2U}\left[\left(\frac{\partial \varphi}{\partial y}\right)^2 + \left(\frac{\partial \varphi}{\partial z}\right)^2\right], z = \zeta(x, y)$$

$$\frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0$$

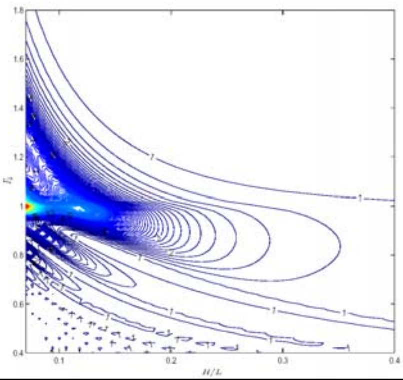




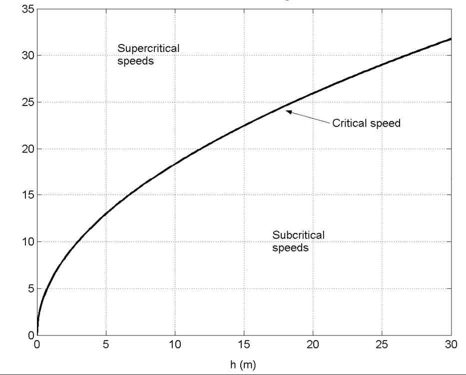
Finite depth effect of residual resistance



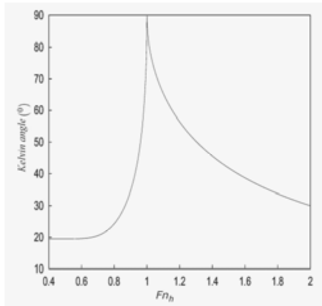
Shallow water wave resistance ratio as a function of H/L and Fh



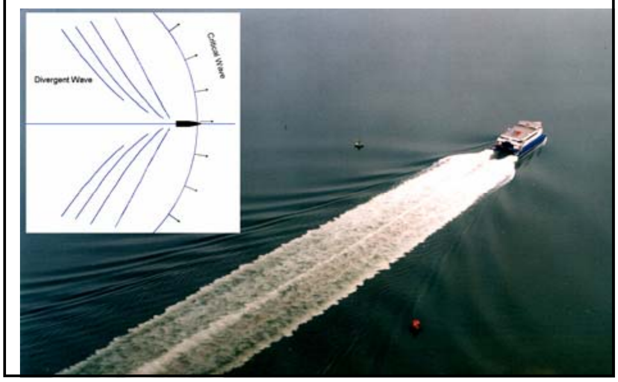
Critical speed as a function of water depth



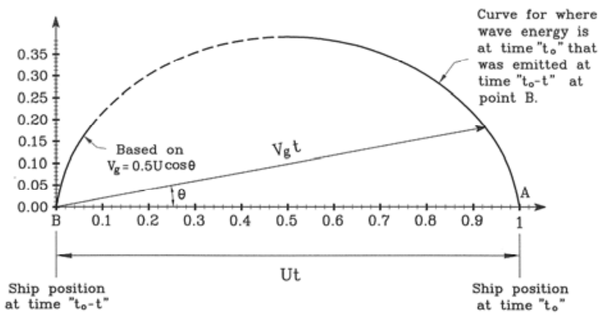
Kelvin angle versus depth Froude number



Wave pattern at critical speed



Propagation of waves at critical speed

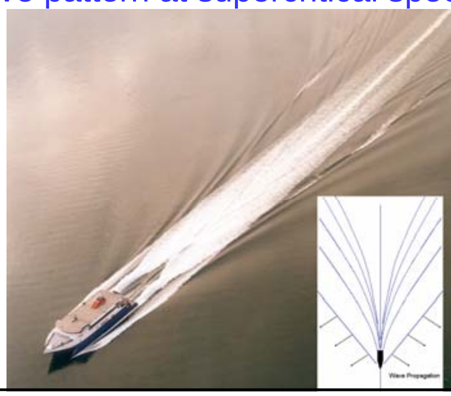


Russel's towing mechanism of 1835

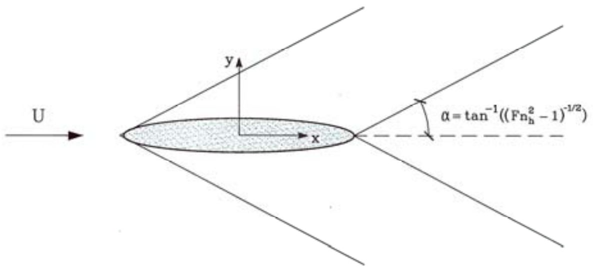
Russel (1865):One day, "the happiest of (his) life, something unexpected happened".

A large,solitary progressive wave occurred ahead of the ship.Could not follow it by foot. Got on the the horseback and followed it for more than a mile

Wave pattern at supercritical speed

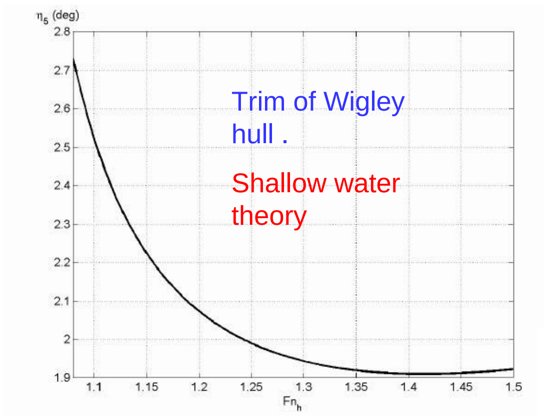


Boundaries of waves at supercritical speed (Tuck)

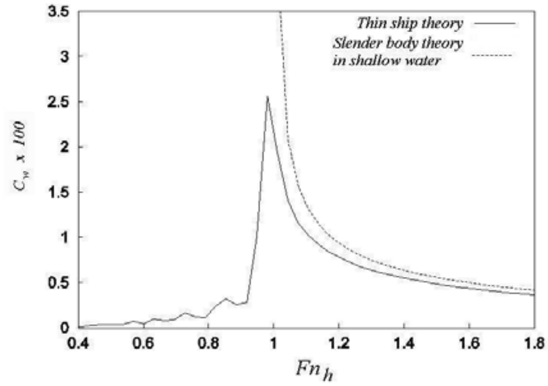


Tuck's shallow water theory. Supercritical speed

- No wave decay (important for wash)
- Wave resistance
- Trim
- No sinkage with fore-aft symmetry

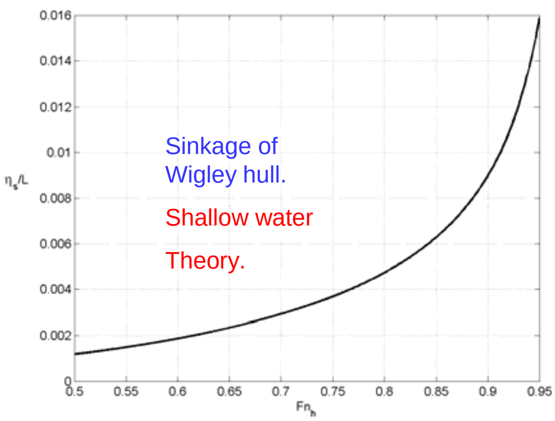


Wave resistance coefficient



Tuck's shallow water theory. Subcritical speed

- No wave generation and wave resistance
- No trim with fore-aft symmetry
- Sinkage



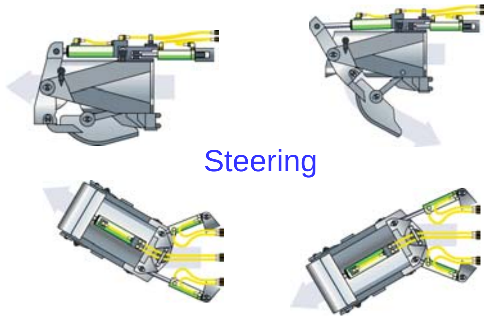
Water jet propulsion

Water jet outlet

Forward thrust

Reverse motion

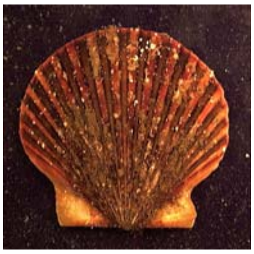
Steering



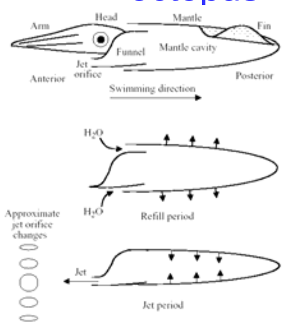
Water jet propulsion in nature

Scallop

- Water jet propulsion
- Up to 6 meters
- 15-20 seconds durability
- Poor maneuverability

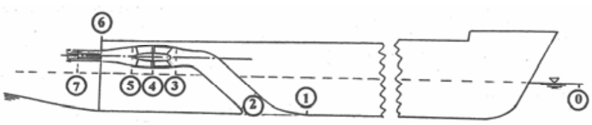


Squid and octopus



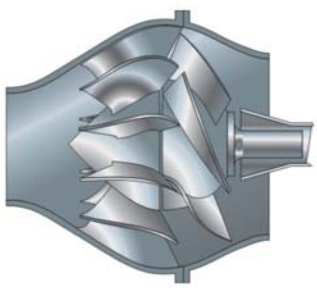
- Jet propulsion
- Undulatory fin motions
- Tentacle 'walking'
- Pumping of lower body

ITTC procedure for model tests

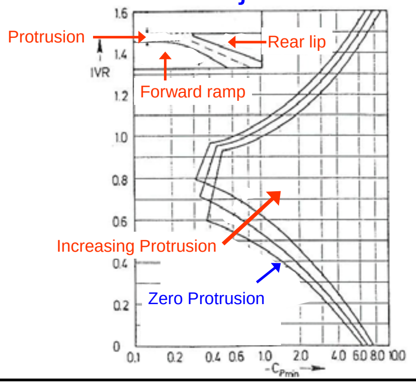


Scaling of inlet flow
Efficiency estimates

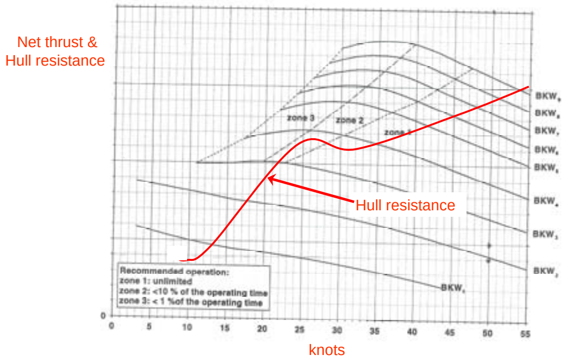
Water jet pump with impeller and stator



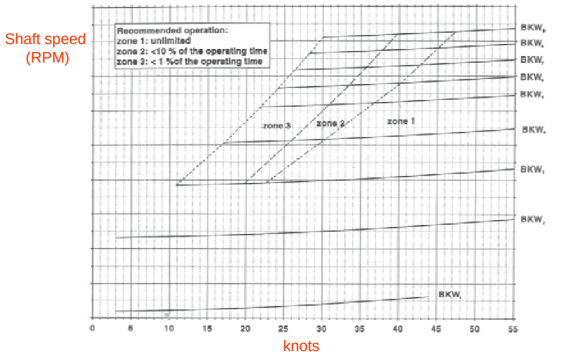
Bucket curves for cavitation in the water jet inlet



Diagrams from waterjet manufacturer



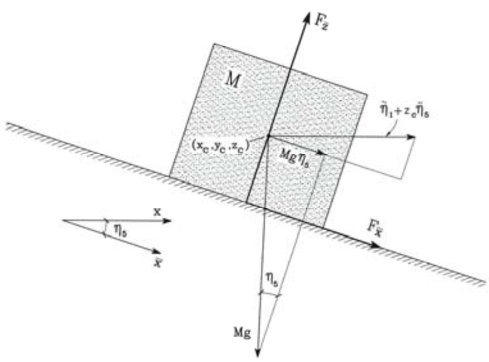
Diagrams from waterjet manufacturer



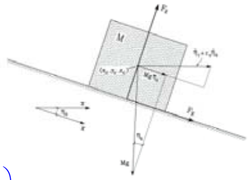
Tractor propeller

Wave induced motions

Wave-induced accelerations of cargo and equipment



Wave-induced accelerations of cargo and equipment



$$M\left(\frac{d^2\eta_1}{dt^2}+z_c\frac{d^2\eta_5}{dt^2}\right)=Mg\eta_5-\mu F_z$$

$$M\left(\frac{d^2\eta_3}{dt^2}-x_c\frac{d^2\eta_5}{dt^2}\right)=-Mg+F_z$$

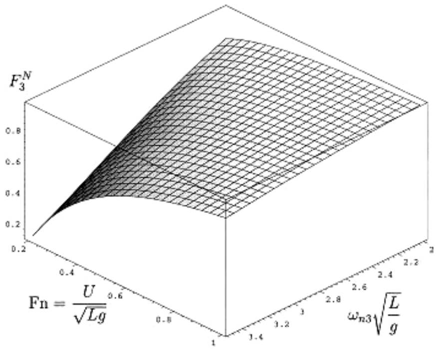
$$a_x=\frac{d^2\eta_1}{dt^2}+z_c\frac{d^2\eta_5}{dt^2}-g\eta_5$$

Wave-induced accelerations of cargo and equipment

- Note linear ship motion calculations are in Earth-fixed coordinate system
- Relative acceleration term is important parameter

$$a_x=\frac{d^2\eta_1}{dt^2}+z_c\frac{d^2\eta_5}{dt^2}-g\eta_5$$

Heave excitation force as a function of Fn



Heave and pitch damping

- Hull-lift damping
- Foil-lift damping
- Viscous damping ?
- Wave radiation damping

Hull lift damping in heave at high frequencies

Vertical hydrodynamic force per unit length:

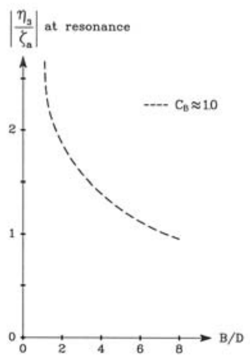
$$f_3=-\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)\left[a_{33}\frac{d\eta_3}{dt}\right]$$

Total vertical hydrodynamic force by integration:

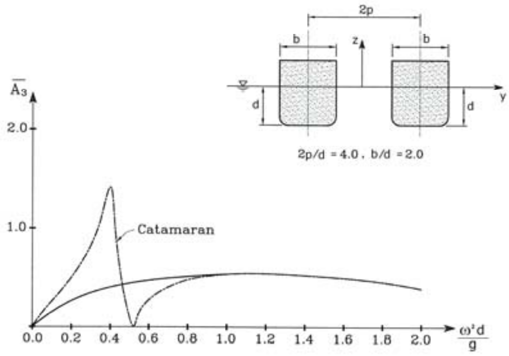
$$F_3=-A_{33}\frac{d^2\eta_3}{dt^2}-B_{33}\frac{d\eta_3}{dt},\ B_{33}=Ua_{33}(x_T)$$

Similar as low-aspect ratio lifting surface theory.
The angle of attack is minus heave velocity divided by U

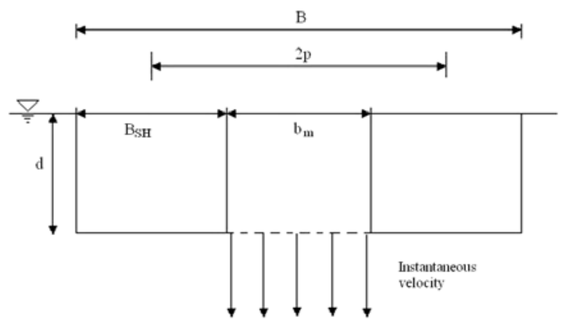
Resonant heave in beam sea versus beam-draft ratio at Fn=0



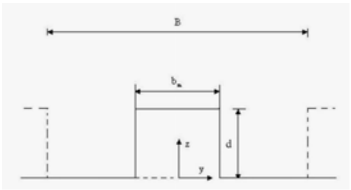
Wave amplitude due to heave (Ohkusu)



Piston mode resonance (Molin)

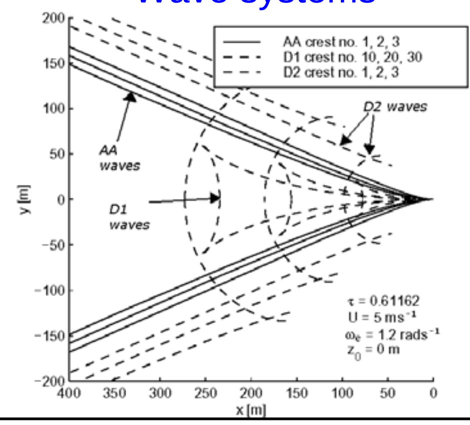


Piston mode resonance frequency

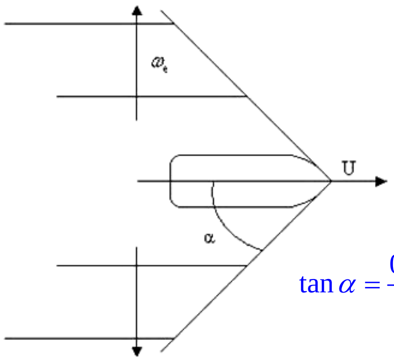


$$\omega_n\sqrt{\frac{d}{g}} = \sqrt{\frac{1}{1+\frac{b_m}{\pi d}\left(1.5+\ln\frac{B}{2b_m}\right)}}$$

Wave systems



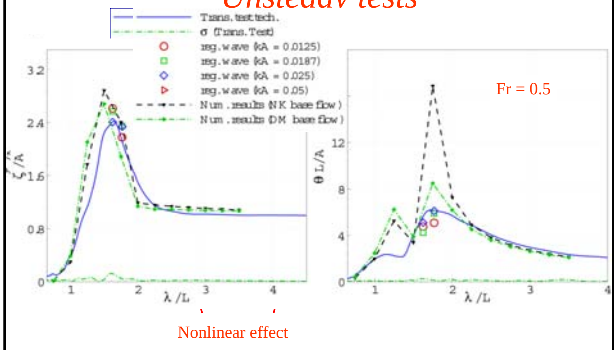
Simplified estimates of wave angle



$$\tan\alpha = \frac{0.5gt/\omega_e}{Ut} = \frac{1}{2\tau}$$

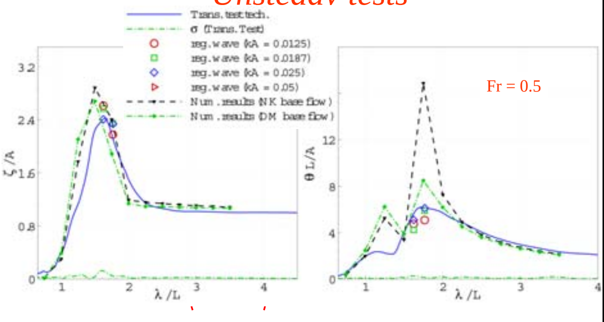
Experimental and Numerical Investigation

Unsteady tests



Experimental and Numerical Investigation

Unsteadv tests

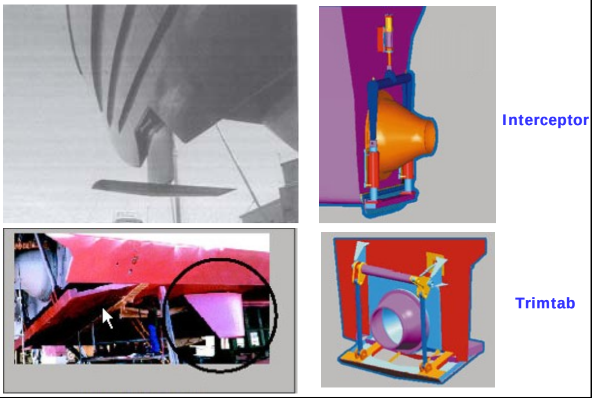


Nonlinear effect

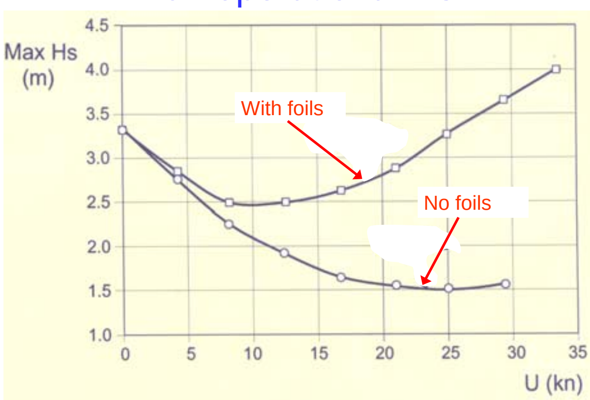
Heave and pitch predictions

- Good agreement between transient testing and regular wave tests
- Differences are due to nonlinear effects
- Small experimental errors
- Interaction between steady and unsteady flow matters in theoretical predictions
- Large resonant motions. One reason is small beam-draft ratio of demihulls

Motion control



Max operational Hs



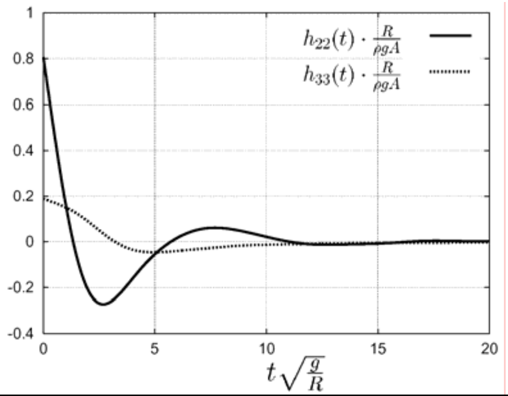
Time domain simulations

- Convolution integrals and retardation function
- Direct numerical simulations

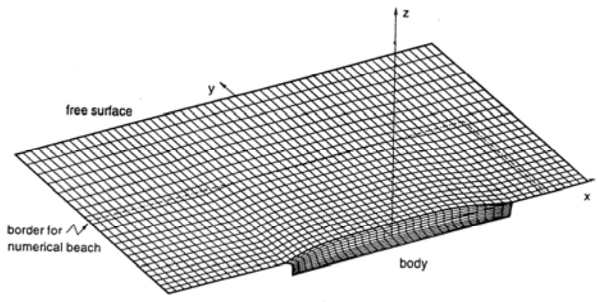
Convolution integrals and retardation functions in time domain equations

$$\int_0^t h_{ij}(\tau)\dot{\eta}_j(t-\tau)d\tau$$

Retardation function



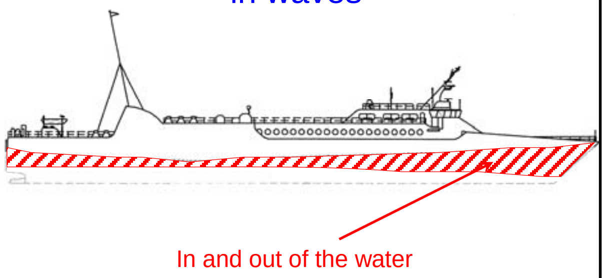
Rankine panel method (Sclavounos)



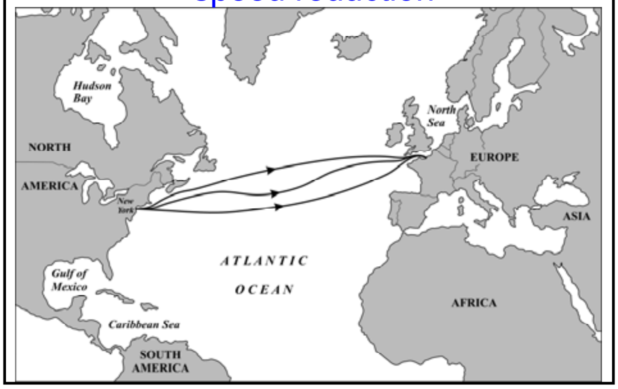
Wave induced motions and loads

- Optimization must include seakeeping
  - Low wave resistance can mean
    - -large vertical ship accelerations (student project)
    - -slamming (Millenium)
- Monohulls:Large length and large beam-draft ratio is beneficial
- Automatic motion control
  - -Small ship motions can mean large global wave loads

Contribution to added resistance in waves

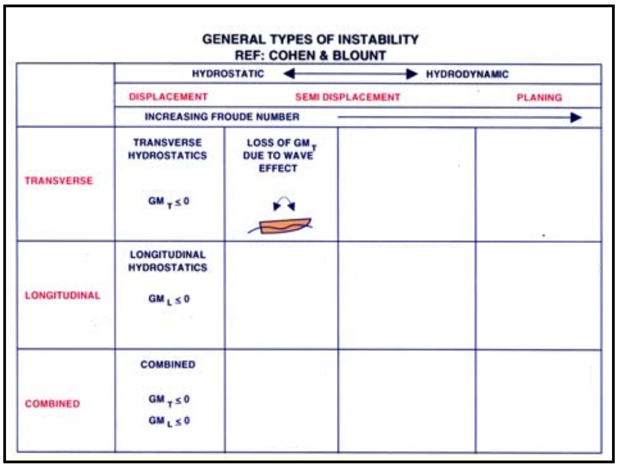


Estimation of involuntary speed reduction



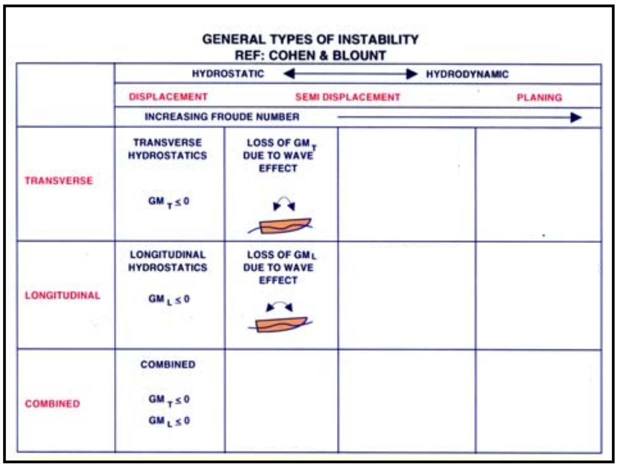
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

		HYDROSTATIC ←→ HYDRODYNAMIC		
		DISPLACEMENT	SEMI DISPLACEMENT	PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \leq 0$			
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \leq 0$			
COMBINED	COMBINED $GM_T \leq 0$ $GM_L \leq 0$			



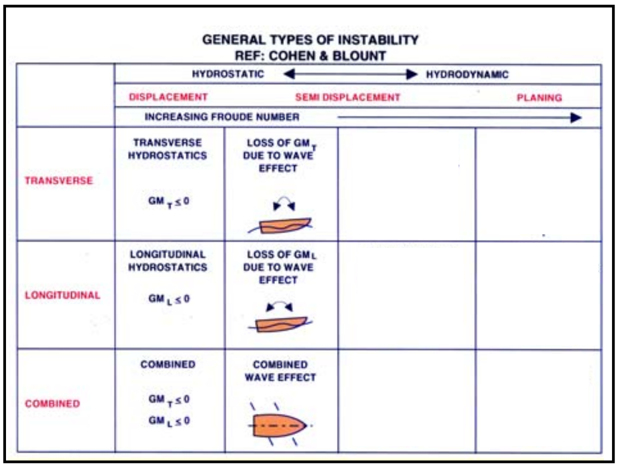
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT		
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$			
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$			



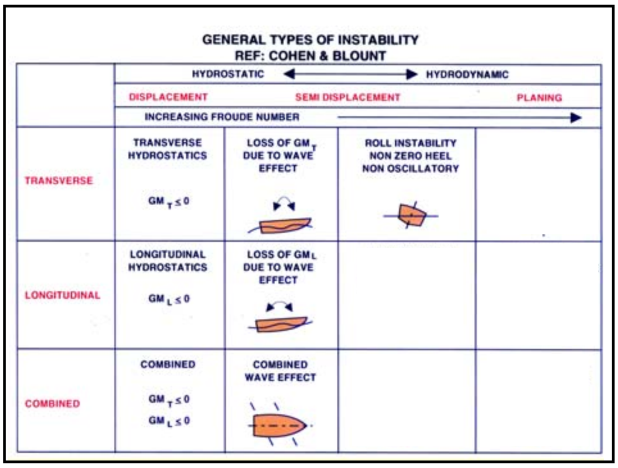
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT		
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT		
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$			



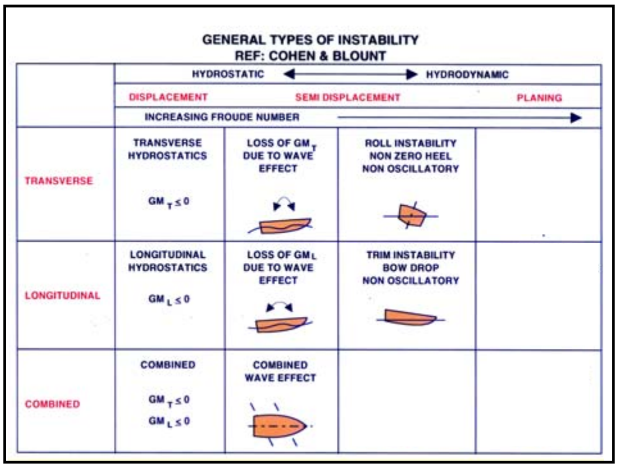
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT		
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT		
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT		



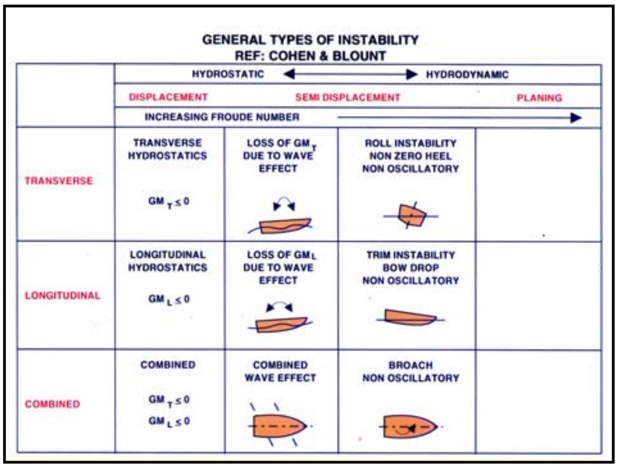
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT		
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT		



GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON OSCILLATORY	
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT		



GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄—► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON OSCILLATORY	
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT	BROACH NON OSCILLATORY	

GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄——► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	"CHINE WALKING" DYNAMIC ROLL OSCILLATION
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON OSCILLATORY	
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT	BROACH NON OSCILLATORY	

GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄——► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	"CHINE WALKING" DYNAMIC ROLL OSCILLATION
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON OSCILLATORY	"PORPOISING" DYNAMIC PITCH-HEAVE OSCILLATION
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT	BROACH NON OSCILLATORY	

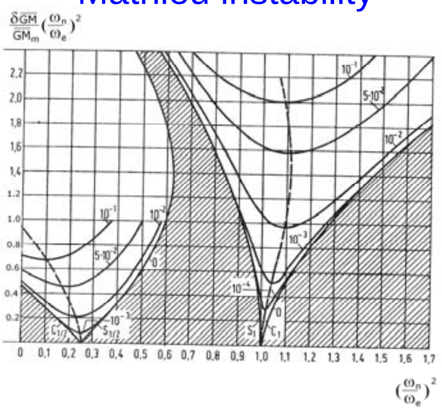
GENERAL TYPES OF INSTABILITY
REF: COHEN & BLOUNT

	HYDROSTATIC ◄——► HYDRODYNAMIC			
	DISPLACEMENT	SEMI DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER →			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \le 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON ZERO HEEL NON OSCILLATORY	"CHINE WALKING" DYNAMIC ROLL OSCILLATION
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \le 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON OSCILLATORY	"PORPOISING" DYNAMIC PITCH-HEAVE OSCILLATION
COMBINED	COMBINED $GM_T \le 0$ $GM_L \le 0$	COMBINED WAVE EFFECT	BROACH NON OSCILLATORY	"CORKSCREW" PITCH-YAW-ROLL OSCILLATION

Mathieu equation for roll

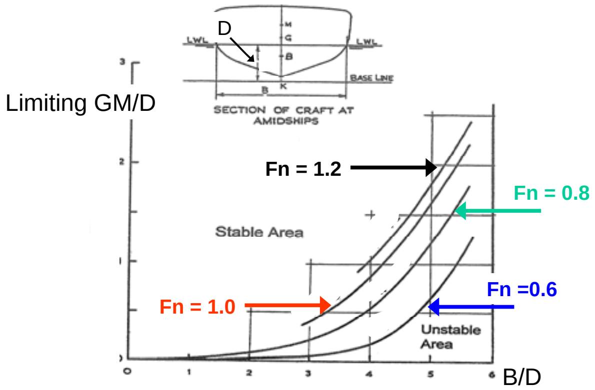
$$\frac{d^2\eta_4}{dt^2} + 2\xi\omega_n \frac{d\eta_4}{dt} + \omega_n^2\left(1 + \frac{\delta GM_m}{GM_m}\sin(\omega_e t + \beta)\right)\eta_4 = 0$$

Mathieu instability

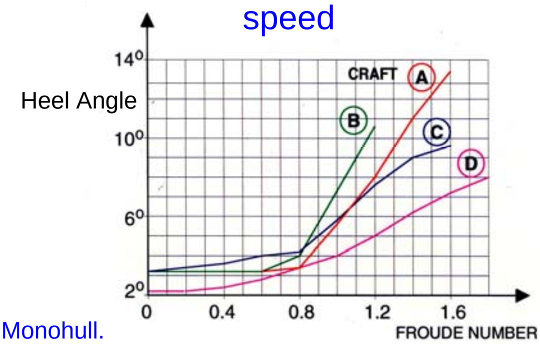


DECK DIVING HIGH-SPEED CATAMARAN FOLLOWING WAVES (WERENSKIOLD)

Steady heel stability of round-bilge hull

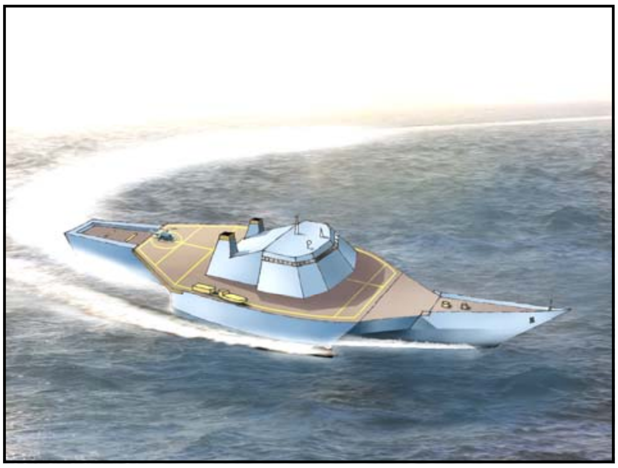


Steady roll stability as a function of speed

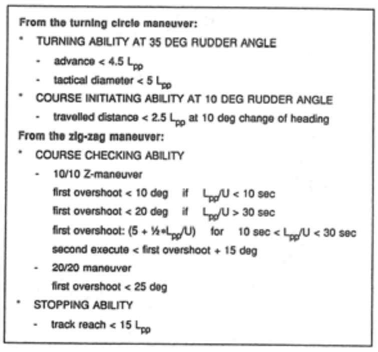


Monohull.

Ref.:Per Werenskiold



Maneuvering criteria. Service speed.Ships >100m. IMO 2002



From the turning circle maneuver:

* TURNING ABILITY AT 35 DEG RUDDER ANGLE
  - advance < 4.5 L_{pp}
  - tactical diameter < 5 L_{pp}
* COURSE INITIATING ABILITY AT 10 DEG RUDDER ANGLE
  - travelled distance < 2.5 L_{pp} at 10 deg change of heading

From the zig-zag maneuver:

* COURSE CHECKING ABILITY
  - 10/10 Z-maneuver

    first overshoot < 10 deg if L_{pp}/U < 10 sec

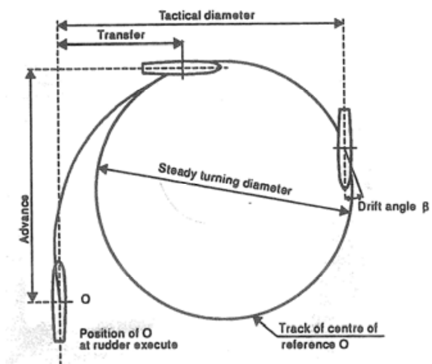
    first overshoot < 20 deg if L_{pp}/U > 30 sec

    first overshoot: (5 + ½·L_{pp}/U) for 10 sec < L_{pp}/U < 30 sec

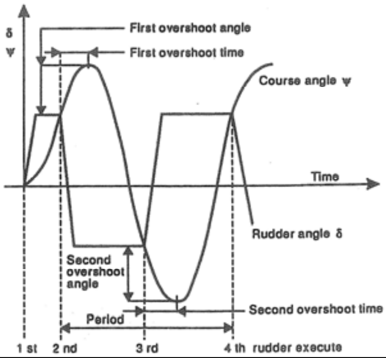
    second execute < first overshoot + 15 deg
  - 20/20 maneuver

    first overshoot < 25 deg
* STOPPING ABILITY
  - track reach < 15 L_{pp}

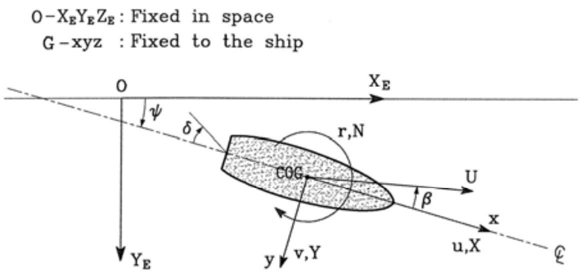
Turning circle manuver



Zig-zag maneuver



Maneuvering definitions



Maneuvering and slender body theory (Newman)

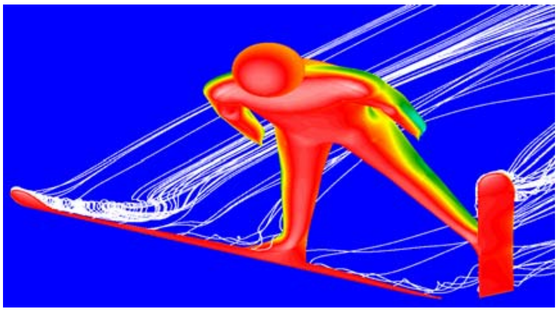
- Moderate speed, i.e rigid free surface condition
- Body-fixed coordinate system
- Linear sway and yaw
- Transverse force per unit length :

$$f_2^{HD} = -\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)\left[a_{22}\left(\dot{\eta}_2 + x\dot{\eta}_6\right)\right]$$

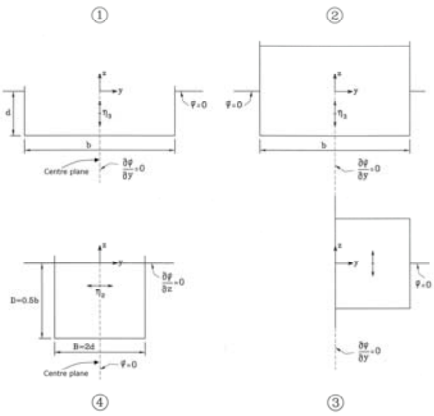
Total transverse force and yaw moment contain important transom stern effects due to low-aspect ratio lifting effects

Other examples on low aspect ratio lifting surfaces

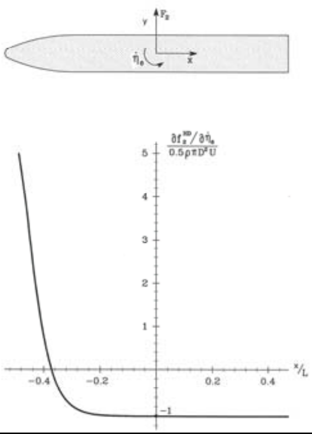
Other examples on low aspect ratio lifting surfaces



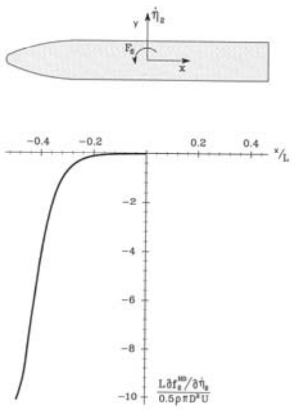
Transform of the infinite frequency heave problem to the low-frequency sway problem



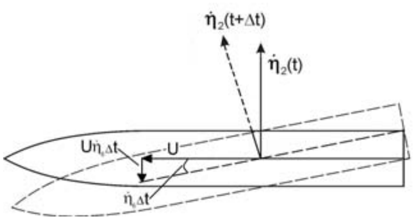
Steady transverse force per unit length due to yaw velocity



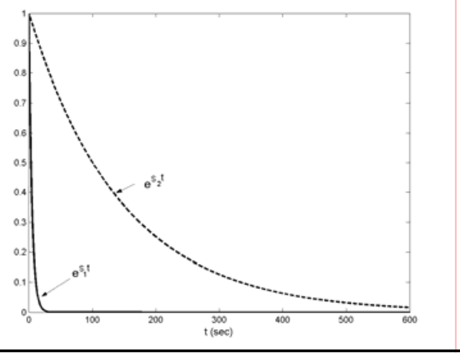
Steady transverse force per unit length due to sway velocity



Ship velocities in body-fixed coordinate system decomposed in an inertial system



Time decay of eigensolutions for sway and yaw

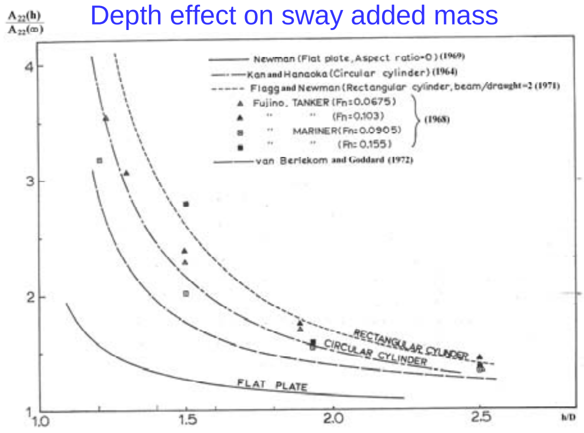


Newman's directional stability criterion

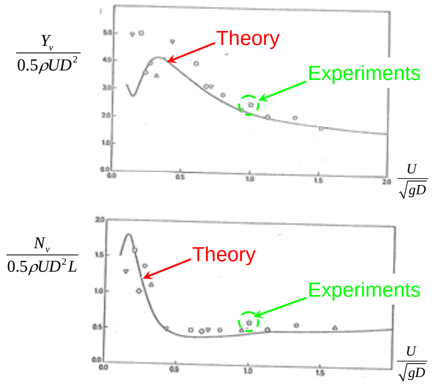
- Moderate speed
- Deep water
- Infinite horizontal extent

$$|x_T| a_{22}(x_T) > \frac{MA_{22}}{M + A_{22}}$$

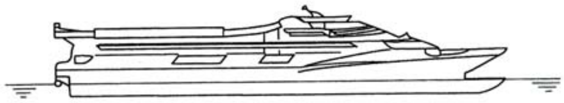
Depth effect on sway added mass



Hydrodynamic derivative terms

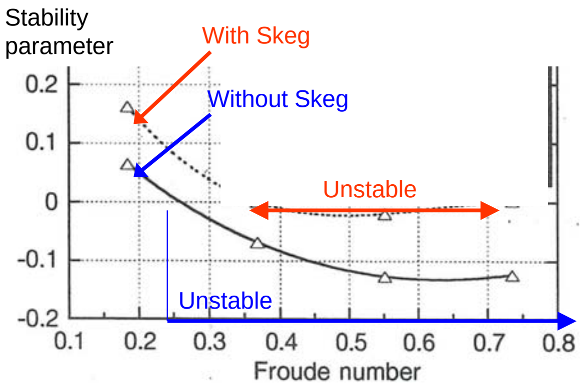


Maneuvering experiments
Directional stability

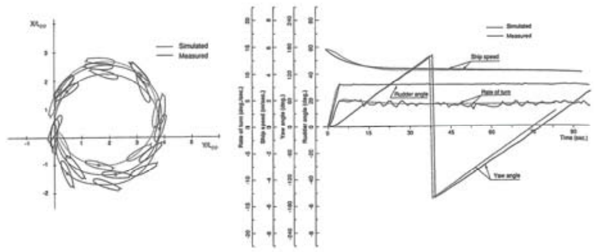


Water Jet Version

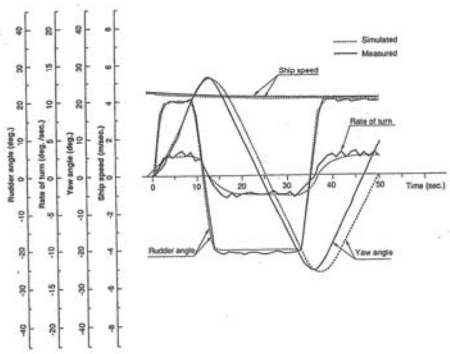
L_{pp} : 2.000 m
B(Twin Hull) : 0.333 m
draught : 0.051 m



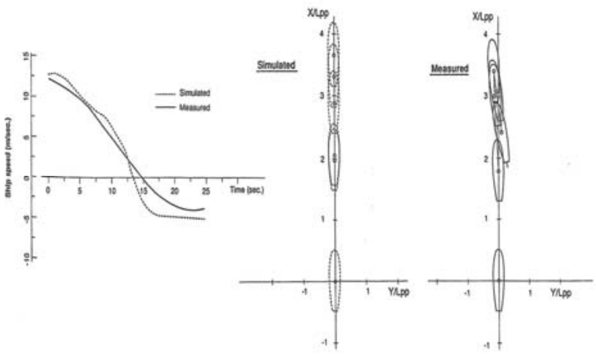
Turning test with the twin hull vessel SSTH



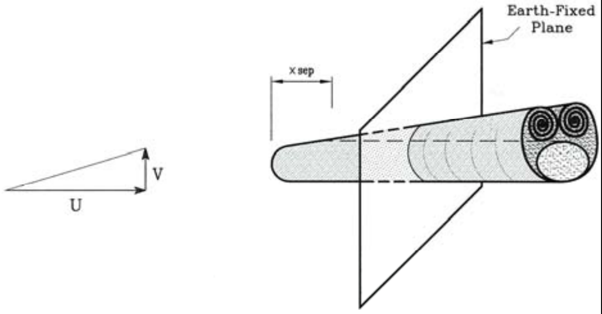
Zig-zag maneuver test with the twin hull vessel SSTH



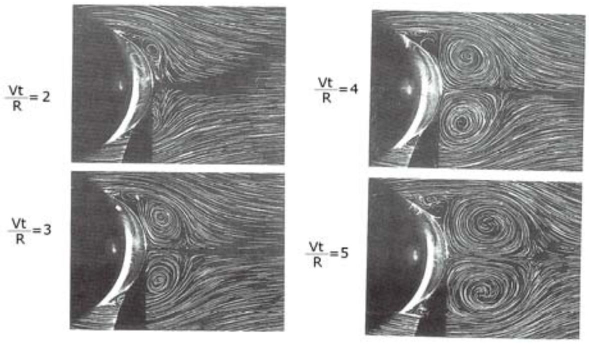
Crash astern test with the twin hull vessel SSTH



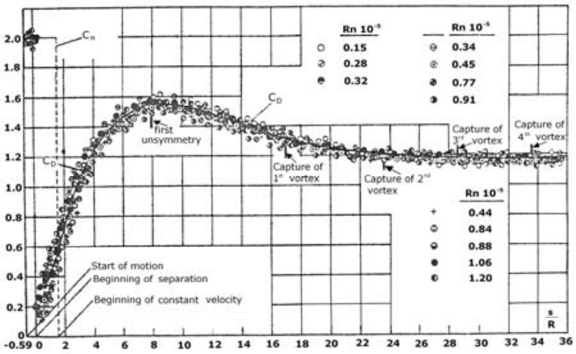
Viscous effects at moderat Fn. 2D+t analysis



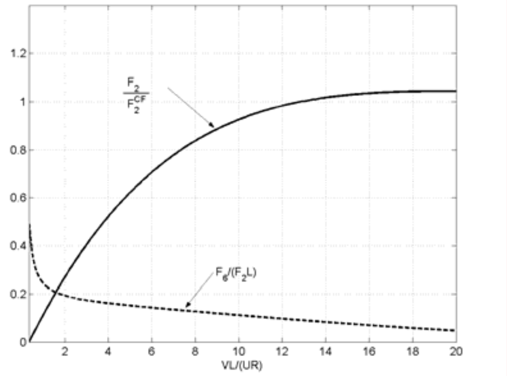
Wake development for impulsively started cylinder



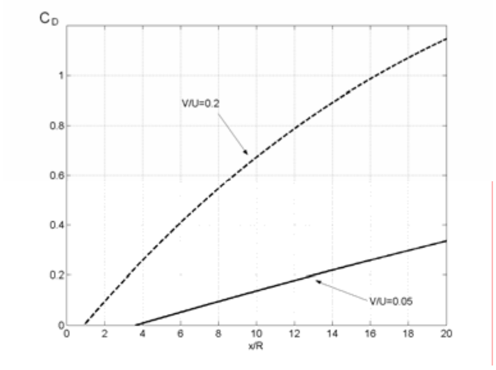
Drag coefficient for impulsively started cylinder (Sarpkaya)



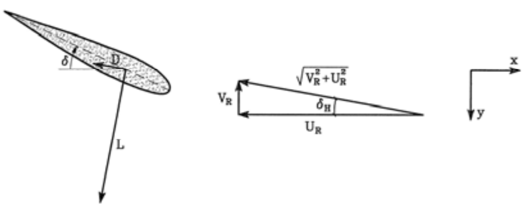
Sway force and yaw moment. 2D+t



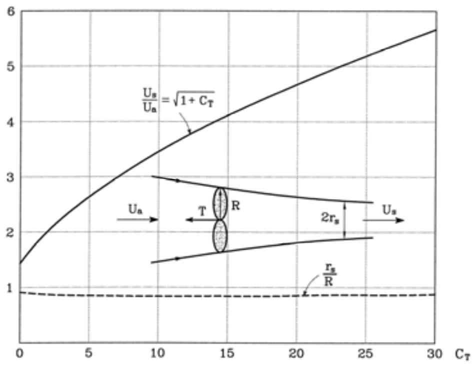
Longitudinal distribution of drag coefficient



Hydrodynamic lift(L) and drag(D) on an all-movable rudder



Axial slip stream velocity behind a propeller

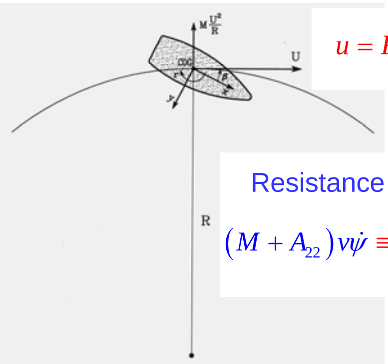


Speed loss due to maneuvering

- Body-fixed coordinate system
- Double-body approximation, i.e. moderate speed
- Added mass theory for non-lifting body in infinite fluid

$$M\left(\dot{u} - v\dot{\psi}\right) = -A_{11}\dot{u} - R_T\left(u\right) + \left(1-t\right)T(u,n)$$
$$+A_{22}v\dot{\psi} + A_{26}\dot{\psi}^2 + X_{\delta\delta}\delta^2$$

Speed loss in turning



$$u = R\dot{\psi}, v \approx -u\beta$$

Resistance term:

$$\left(M + A_{22}\right)v\dot{\psi} \equiv -\left(M + A_{22}\right)\frac{u^2}{R}\beta$$

Effect of forward speed

- Wave generation
- Sinkage and trim
- Coupled sway,yaw and heel with speed reduction

Maneuvering of trimaran

- Strong nonlinearities may occur
- Heel may cause sign change in yaw moment at relatively small heel angles

Broaching of catamaran in quartering sea