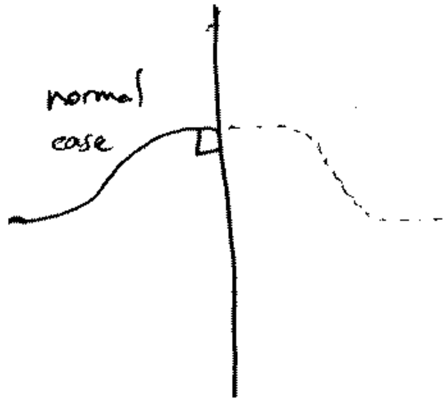
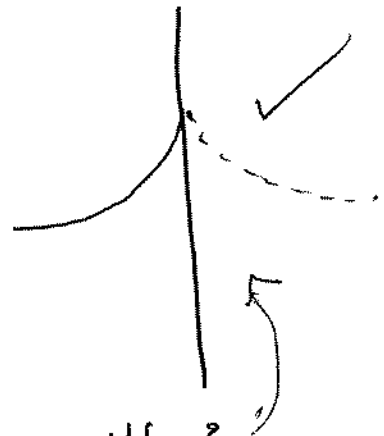
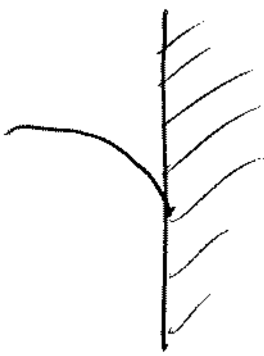
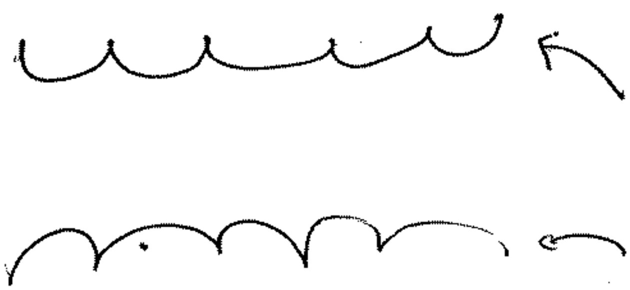
S. Wu: Supplementary Boardwork



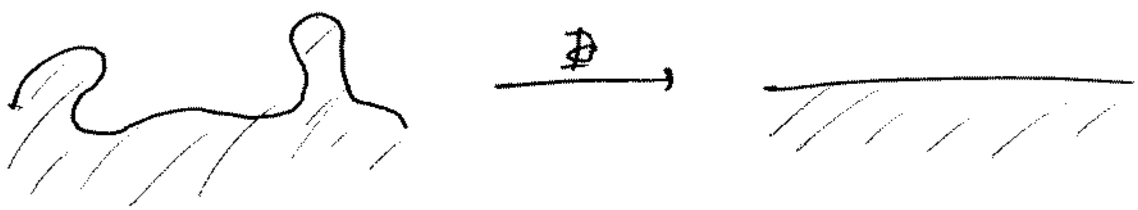


Q: Angle other than normal possible?



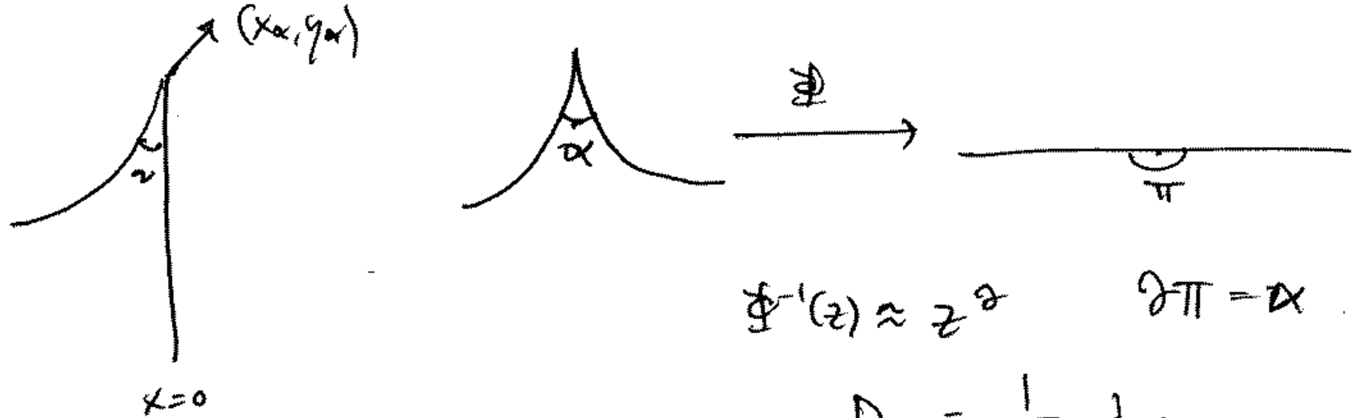


$$\Phi(\cdot,t),\ \Omega(t) \longrightarrow P_-$$



$$h(\alpha,t) = \Phi(z(\alpha,t),t)$$

$$\int_{\partial\Omega} u \cdot \frac{\partial u}{\partial n} = \int_{\Omega} |\nabla u|^2 \geq 0$$

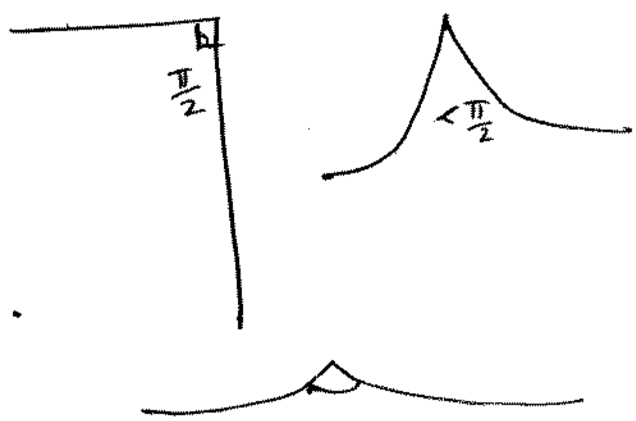


$\Phi^{-1}(z) \approx z^{\nu}$ $\qquad \nu\pi = \alpha$

$$D_{\alpha'} = \frac{1}{Z_{,\alpha'}} \partial_{\alpha'}$$

$Z_{,\alpha'} \sim \alpha^{r-1}$

$\frac{1}{Z_{,\alpha}} = 0$ at singularity



On two dimensional gravity water waves with angled crests

Sijue Wu

University of Michigan, Ann Arbor

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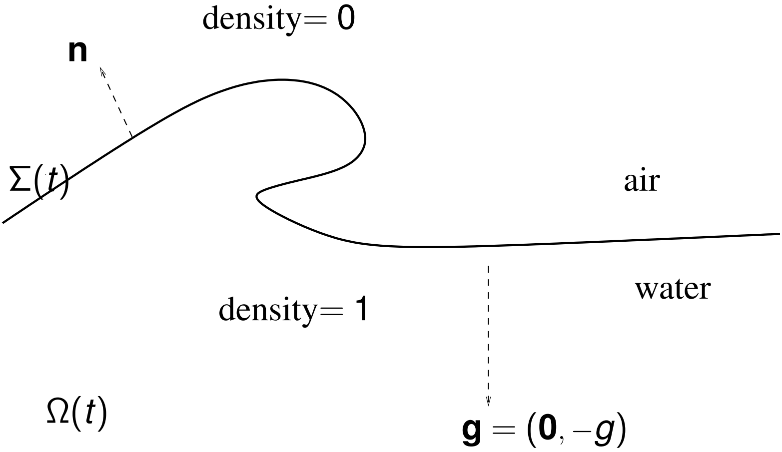
We consider the motion of the interface separating air from water.

We assume:

- air density= 0
- water density =1
- water region is below the air region. At time t, water region is $\Omega(t)$, the interface is $\Sigma(t)$.

We assume that the water is

- inviscid, incompressible, irrotational.
- The surface tension is zero.
- The water is subject to the influence of gravity $\mathbf{g} = (\mathbf{0}, -g)$.
- $g > 0$


density= 0
n
Σ(t)
air
water
density= 1
Ω(t)
g = (0, −g)

The motion of the fluid is described by

$$\begin{cases} \mathbf{v}_t + \mathbf{v} \cdot \nabla \mathbf{v} = (\mathbf{0}, -g) - \nabla P & \text{in } \Omega(t) \\ \operatorname{div} \mathbf{v} = 0, \qquad \operatorname{curl} \mathbf{v} = 0, & \text{in } \Omega(t) \\ P = 0, & \text{on } \Sigma(t) \end{cases} \tag{1}$$

$\mathbf{v}$ is the fluid velocity, P is the fluid pressure.

When surface tension is zero, the motion can be subject to the Taylor instability.

- Taylor sign condition:

$$-\frac{\partial P}{\partial \mathbf{n}} \geq 0$$

  on the interface $\Sigma(t)$. $\mathbf{n}$ is the unit normal to $\Sigma(t)$ pointing out of the water region $\Omega(t)$.

earlier work

Stokes, Levi-Civita, Taylor....

Local wellposedness in Sobolev spaces

- Nalimov (1974): infinite depth, 2D, assume initial interface flat, initial velocity small
- Nalimov didn't use Riemann mapping
- T. Nishida: translated Nalimov's paper into English,
- Yoshihara (1982): finite depth, 2D, assume initial data small
- T. Beale, T. Hou & Lowengrub (1992).
  Linear wellposedness assuming the presumed solution satisfies the strong Taylor sign condition:

$$-\frac{\partial P}{\partial \mathbf{n}} \geq c_0 > 0.$$

Local wellposedness in Sobolev spaces continues...

- S. Wu (1997, 99): 2D, 3D, arbitrary data
- proved the strong Taylor sign condition always holds, i.e.

$$-\frac{\partial P}{\partial \mathbf{n}} \geq c_0 > 0$$

as long as the interface is non-selfintersecting and smooth ($C^{1,\gamma}$).

- in 2D: used Riemann mapping to understand the quasilinear structure of the water wave equation
- in 3D: used Lagrangian coordinates, in Clifford algebra framework

local wellposedness continues....

Local wellposedness with additional effects: nonzero surface tension, finite depth, nonzero vorticity, assuming the strong Taylor sign condition holds.

- Iguchi(2001), Ogawa & Tani (2002), Ambrose & Masmoudi(2005), D. Lannes (2005), Christodoulou & Lindblad (2000), Lindblad (2005), Coutand & Shkoller (2007), P. Zhang & Z. Zhang (2007), Shatah & Zeng (2008)

Global behavior for small, smooth and localized data

- S. Wu (2009): almost global well-posedness for 2-D,
- S. Wu (2011): global well-posedness for 3-D
- Germain, Masmoudi & Shatah (2012): global well-posedness for 3-D
- Ionescu & Pusateri (2013): 2-D water waves, global existence and modified scattering
- Alazard & Delort (2013): similar result
- Hunter, Ifrim & Tataru (2014): 2-D water wave, almost global existence, modified energy method
- Ifrim & Tataru (2014): 2-D water wave, global existence.

local wellposedness in low regularity Sobolev spaces:

- Alazard, Burq, Zuily (2012): Local wellposedness in low regularity Sobolev space–the interface is $C^{3/2+\epsilon}$.
- Alazard, Burq, Zuily (2014): Local wellposedness in low regularity Sobolev space–the interface is $C^{3/2-\epsilon}$.

Singularities:

Singularities:

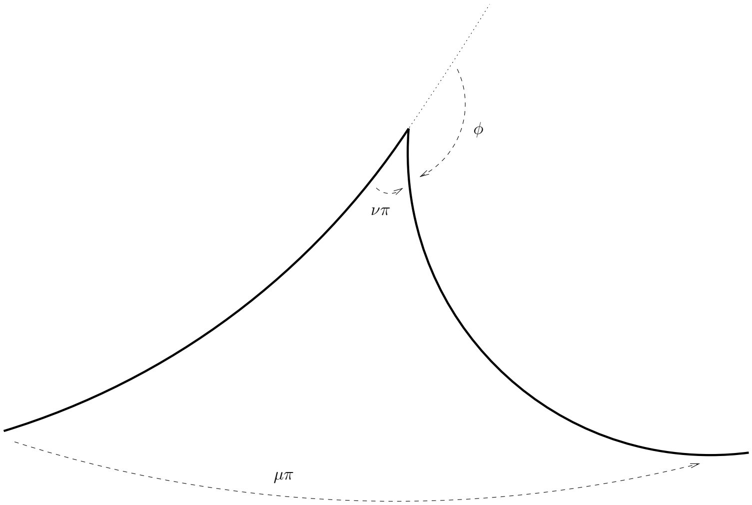
What are some typical singular behaviors? How does it form? What are some basic structures of the singularities?

Self-similar solutions:

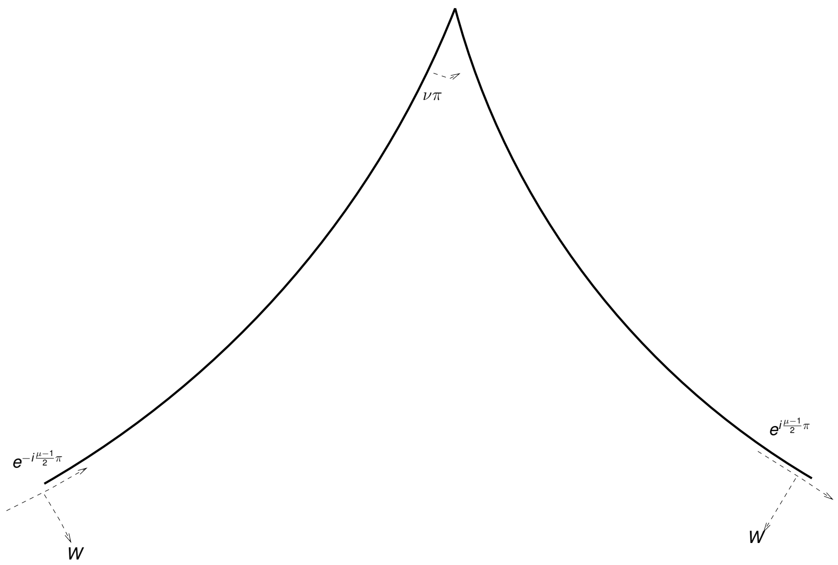
S. Wu (2012): construction of self-similar solution for 2-D water waves in the regime where convection is in dominance:

- $z \sim t$, or in hyperbolic scaling: $s = 1$.

— neglecting gravity and surface tension.
—- satisfies the Taylor sign condition $-\frac{\partial P}{\partial \mathbf{n}} \geq 0$.


ϕ
$\nu\pi$
$\mu\pi$

- $\nu < \frac{1}{2}, \qquad \mu > \frac{1}{2}$
- concave up on both sides, the concavity is due to the Taylor stability condition.



$\nu\pi$
$e^{-i\frac{\mu-1}{2}\pi}$
$e^{i\frac{\mu-1}{2}\pi}$
W
W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Question:

Q: How relevant are the self-similar solutions?

In all earlier work, either it is assumed there is no bottom, or there is a bottom Υ, of a positive distance away from the interface $\Sigma(t)$

$$dist(\Sigma(t), \Upsilon) \geq h_0 > 0$$

and the strong Taylor sign condition holds:

$$-\frac{\partial P}{\partial \mathbf{n}} \geq c_0 > 0$$

A different take: motivation

Question

We consider the following problem:
Q: the interaction of the free surface with a fixed rigid boundary?

On a rigid smooth boundary,

$$\mathbf{v} \cdot \mathbf{n} = 0$$

In the presence of a fixed rigid boundary Υ, the motion of the fluid is described by

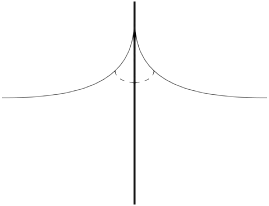
$$\begin{cases} \mathbf{v}_t + \mathbf{v} \cdot \nabla \mathbf{v} = (\mathbf{0}, -g) - \nabla P & \text{in } \Omega(t) \\ \operatorname{div} \mathbf{v} = 0, \qquad \operatorname{curl} \mathbf{v} = 0, & \text{in } \Omega(t) \\ P = 0, & \text{on } \Sigma(t) \\ \mathbf{v} \cdot \mathbf{n} = 0, & \text{on } \Upsilon \end{cases} \tag{2}$$

$\mathbf{v}$ is the fluid velocity, P is the fluid pressure. $\mathbf{n}$ is a normal vector to Υ.

$\partial\Omega(t) = \Sigma(t) \cup \Upsilon$.

We look at the wave motion at a vertical wall:

If the fixed rigid boundary Υ is a vertical wall $\{x = 0\}$, and the fluid domain $\Omega(t)$ is the domain to the right of $\{x = 0\}$. Then the velocity field $\mathbf{v} = (v_1, v_2)$ satisfies $v_1(0, y; t) = 0$.
By Schwarz reflection:
$\mathbf{v}(-x, y; t) = (-v_1(x, y; , t), v_2(x, y; t))$; $P(-x, y; t) = P(x, y, ; t)$
we can reduce the problem to the one on the symmetric domain without a fixed wall.



- Alazard, Burq, Zuily (2012) studied the case where the angle of the wave with the wall is 90°.
- Our focus: study the case where the angle of the wave with the wall is other than 90°.

We want to answer the following question:

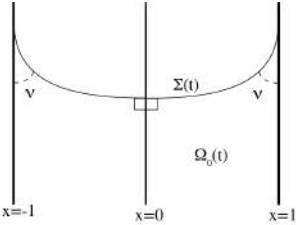
Q: Is it possible for the angle between the interface and the wall to be other than $\frac{\pi}{2}$?

Put it in an infinite depth "cup"...

Assume the rigid boundary Υ is consisting of two vertical walls:

$$\Upsilon = \{x = 0\} \cup \{x = 1\}$$

Assume the free interface $\Sigma(t)$ makes a 90° angle with the wall $\{x = 0\}$, but we allow a possible non-trivial angle at $\{x = 1\}$. We make a Schwarz reflection about $\{x = 0\}$:



- Q: Can the angle ν be other than 90°?
- Q: local existence in this framework?
- A priori estimates?

Main Result (whole line or periodic):

- yes, the angle ν can be other than 90°. If it is not 90°, then
- the angle ν must be no more than 90°. More generally,
- the interior angles of the angled crests (don't have to be symmetric) cannot be more than 180°.

— these facts are determined by the water wave equations.

Main Result (whole line or periodic):

- We construct an analytic framework that includes smooth interfaces, and interfaces with angled crests
- A priori estimates, local existence holds in this regime which includes interfaces with angled crests.
- This is a more fitting framework to study the water wave equation than Sobolev spaces

The water wave system admits such solutions.

- A prior estimate: joint work with Rafe Kinsey.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Difficulty:

In our regime, we can show that

- $-\frac{\partial P}{\partial \mathbf{n}} \geq 0$, but
- $-\frac{\partial P}{\partial \mathbf{n}} = -\mathbf{n} \cdot \nabla P = 0$ at the wall where there is a non-right angle, and at the points on the interface where there are angled crests.
- $\mathbf{n}$ outward unit normal.

why this is a difficulty

Let the free surface be

$$\Sigma(t) : z = z(\alpha, t), \quad \alpha \text{ Lagrangian coordinate.}$$

- $z = x(\alpha, t) + iy(\alpha, t)$, in complex form;
- $z_t = z_t(\alpha, t)$ is the velocity;
- z_{tt} is the acceleration;
- $-i$ is the gravity;
- $P = 0$ on $\Sigma(t)$ implies: $\nabla P \perp \Sigma(t)$
- $\nabla P = i\mathfrak{a} z_\alpha$, where $\mathfrak{a} = -\frac{1}{|z_\alpha|}\frac{\partial P}{\partial \mathbf{n}}$

Wu (1997, 99):

- div $\mathbf{v} = \text{curl } \mathbf{v} = 0$ implies $\bar{\mathbf{v}}$ is holomorphic in $\Omega(t)$.
- $\bar{z}_t(\alpha, t) = \bar{\mathbf{v}}(z(\alpha, t), t)$, the boundary value of the holomorphic function $\bar{\mathbf{v}}$.
- $\bar{z}_t = \mathfrak{H}\bar{z}_t$

  Equation of the free surface:

$$\begin{cases} z_{tt} + i = i\mathfrak{a}z_\alpha \\ \bar{z}_t = \mathfrak{H}\bar{z}_t \end{cases} \tag{3}$$

Wu (1997,99)

Quasilinear equation:

$$\bar{z}_{ttt} + i\mathfrak{a}\bar{z}_{t\alpha} = -i\mathfrak{a}_t\bar{z}_\alpha$$

Let

- $\mathfrak{u} = \bar{z}_t$
- $i\bar{z}_{t\alpha} = \nabla_{\mathbf{n}}\mathfrak{u}$

Free surface equation:

$$(\partial_t^2 + \mathfrak{a}\nabla_{\mathbf{n}})\mathfrak{u} = l.o.t$$

is degenerate hyperbolic, if $\mathfrak{a} = -\frac{1}{|z_\alpha|}\frac{\partial P}{\partial \mathbf{n}}$ can be zero.

work in Wu (1997):

$$\mathfrak{H} f(\alpha; t) = \frac{1}{\pi i} \int \frac{z_\beta(\beta; t)}{z(\alpha; t) - z(\beta; t)} f(\beta)\, d\beta$$

- difficult to deal with $\mathfrak{H}$
- Use Riemann mapping

Interface equation in Riemann mapping variable

- Let $\Phi : \Omega(t) \to P_-$ be the Riemann mapping, s.t. $\lim_{z\to\infty} \Phi_z(z) = 1$.
- P_- is the lower half plane
- Let $h(\alpha; t) := \Phi(z(\alpha; t); t)$.
- h^{-1} be: $\quad h(h^{-1}(\alpha'; t); t) = \alpha'$
- $Z(\alpha'; t) = z(h^{-1}(\alpha'; t), t) := z \circ h^{-1}$; $Z_{,\alpha'} = \partial_{\alpha'} Z(\alpha', t)$
- $Z_t(\alpha'; t) := z_t \circ h^{-1}$; $Z_{tt}(\alpha'; t) := z_{tt} \circ h^{-1}$

Wu (1997):

Let

- $A \circ h = \mathfrak{a} h_\alpha$
- $\mathbb{H} f(\alpha') = \frac{1}{\pi i} \int \frac{1}{\alpha' - \beta'} f(\beta')\, d\beta'$ be the Hilbert transform

Free surface equation in Riemann mapping variable α':

$$\begin{cases} Z_{tt} + i = iAZ_{,\alpha'} \\ \overline{Z}_t = \mathbb{H}\overline{Z}_t \end{cases} \tag{4}$$

work in Wu (1997)

$h(\alpha;t) := \Phi(z(\alpha;t);t)$ implies that

$$Z(\alpha',t) = \Phi^{-1}(\alpha';t); \quad Z_{,\alpha} = \partial_{z'}\Phi^{-1}(\alpha';t)$$

- To Show the Taylor sign condition $-\frac{\partial P}{\partial \mathbf{n}} \geq c_0 > 0$,

$$-i\frac{\partial P}{\partial \mathbf{n}}|Z_{,\alpha'}| = \overline{Z}_{,\alpha'}(Z_{tt}+i) = iA|Z_{,\alpha'}|^2 := iA_1$$

we proved in Wu (1997) that

$$A_1 = 1 + \frac{1}{2\pi}\int \frac{|Z_t(\alpha',t) - Z_t(\beta',t)|^2}{(\alpha'-\beta')^2}\,d\beta' \geq 1$$

Wu (1997)

- $$-\frac{\partial P}{\partial \mathbf{n}} = \mathfrak{a}|z_\alpha| = \frac{A_1}{|Z_{,\alpha'}|} \circ h \geq 0$$

  Recall: $Z_{,\alpha'} = \partial_{z'} \Phi^{-1}(\alpha'; t)$
- (S.Wu, 1997) If the interface $\Sigma(t) \in C^{1,\gamma}$, then $0 < c_0 \leq |\partial_{z'} \Phi^{-1}(\alpha'; t)| \leq C_0 < \infty$, then

$$-\frac{\partial P}{\partial \mathbf{n}} \geq c_1 > 0$$

$$\frac{1}{Z_{,\alpha'}} = i\frac{\overline{Z}_{tt} - i}{A_1}$$

$\mathfrak{a} = 0$ or equivalently $-\frac{\partial P}{\partial \mathbf{n}} = 0$ at the corner:

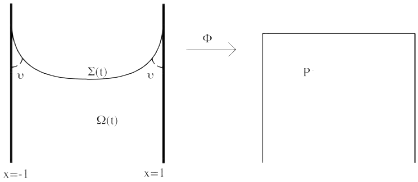
Free surface equation: $z_{tt} + i = i\mathfrak{a}z_\alpha := \nabla P$, $\mathfrak{a} \in \mathbb{R}$ implies:

$$-\frac{x_\alpha}{y_\alpha} = \frac{y_{tt}+1}{x_{tt}}. \tag{5}$$

$$\tan\nu = -\frac{x_\alpha}{y_\alpha} = \frac{y_{tt}+1}{x_{tt}}. \tag{6}$$

- $x_t(0;t) = 0$ implies $x_{tt}(0;t) = 0$.
- If $\nu \neq \frac{\pi}{2}$, then $y_{tt} + 1 = 0$ at $x = 0$.
- Therefore $\nabla P = 0$ at the corner $x = 0$.
- $\mathfrak{a} = 0$ at the corner $x = 0$.

- Fact 1: $\nu \leq \frac{\pi}{2}$
- at the corner:
  $\Phi^{-1}(z') \approx (z')^r$, where $\nu = \frac{\pi}{2} r$.
- $Z_{,\alpha'} = \partial_{z'} \Phi^{-1}(z') \approx (\alpha')^{r-1}$.
- if $\nu > \frac{\pi}{2}$, i.e. if $r > 1$, then $Z_{,\alpha} = 0$ at the corner, so $Z_{tt} = \infty$, so $y_{tt} = \infty$ at the corner, since $x_{tt} = 0$,



Recall

$$\tan\nu = -\frac{x_\alpha}{y_\alpha} = \frac{y_{tt}+1}{x_{tt}}. \tag{7}$$

this implies

$$\tan\nu = \infty$$

therefore

$$\nu = \frac{\pi}{2}$$

So ν cannot be greater than $\frac{\pi}{2}$.
Similarly,

- Interior angle of the angled crests cannot be more than π.

- Fact 2:
$$-\frac{\partial P}{\partial \mathbf{n}} = \mathfrak{a}|z_\alpha| = \frac{A_1}{|Z_{,\alpha'}|} \circ h \geq 0$$
Recall: $Z_{,\alpha'} = \partial_{z'} \Phi^{-1}(\alpha'; t)$
- If the angle $\nu < \frac{\pi}{2}$, or if the free surface has angled crests with interior angle $< \pi$, then $r < 1$, then $\frac{1}{Z_{,\alpha'}} \to 0$ at the corner or at the crests, this implies
$$-\frac{\partial P}{\partial \mathbf{n}} = 0$$
at the corner if $\nu < \frac{\pi}{2}$ and at the crests where the interior angle is $< \pi$.

The energy functional

Let

$$D_\alpha f = \frac{1}{z_\alpha}\partial_\alpha f, \quad D_{\alpha'} g = \frac{1}{Z_{,\alpha'}}\partial_{\alpha'} g$$

If f is the boundary value of a periodic holomorphic function F on $\Omega(t)$, $f(\alpha, t) = F(z(\alpha, t), t)$, then

$$D_\alpha f = \partial_z F(z(\alpha, t); t) = -i\partial_y F(z(\alpha, t); t)$$

Recall the quasilinear equation of the free surface:

$$(\partial_t^2 + i\mathfrak{a}\partial_\alpha)\bar{z}_t = -i\mathfrak{a}_t\bar{z}_\alpha, \tag{8}$$

higher order equation

$$(\partial_t^2 + i\mathfrak{a}\partial_\alpha)\theta = G_\theta. \tag{9}$$

where $\theta = D_\alpha^k \bar{z}_t$, $G_\theta = D_\alpha^k(-i\mathfrak{a}_t\bar{z}_\alpha) + [\partial_t^2 + i\mathfrak{a}\partial_\alpha, D_\alpha^k]\bar{z}_t$.
a natural energy:

- $e = \int |\theta_t|^2 + \Re \int (i\mathfrak{a}\partial_\alpha\theta)\bar{\theta}$

doesn't work in the framework of angled crests.

We construct the energy: let $\alpha_0 \in [-1, 1]$ be fixed

$$E = E_{a,D_\alpha^2 \bar{z}_t} + E_{b,D_\alpha \bar{z}_t} + \|\bar{z}_{tt}(t) - i\|_{L^\infty}$$

where

$$E_{a,\theta} = \int_{-1}^{1} \frac{h_\alpha}{A_1 \circ h} |\theta_t|^2 \, d\alpha + \Re \int_{-1}^{1} \frac{h_\alpha}{A_1 \circ h} (i\mathfrak{a}\partial_\alpha \theta)\bar{\theta} \, d\alpha + l.o.t.$$

$$E_{b,\theta} = \int_{-1}^{1} \frac{1}{\mathfrak{a}} |\theta_t|^2 \, d\alpha + \Re \int_{-1}^{1} (i\partial_\alpha \theta)\bar{\theta} \, d\alpha + l.o.t.$$

$$\mathfrak{a} \approx h_\alpha \approx -\frac{\partial P}{\partial \mathbf{n}}$$

E_a and E_b have roughly inverse singular weights h_α and $\frac{1}{\mathfrak{a}}$.

$$A_1 \circ h = \frac{\mathfrak{a}|z_\alpha|^2}{h_\alpha}$$

A characterization of the energy functional

Let

$$\mathcal{E}(t) = \|\bar{Z}_{t,\alpha'}\|_{L^2}^2 + \|D_{\alpha'}^2 \bar{Z}_t\|_{L^2}^2 + \|\partial_{\alpha'} \frac{1}{Z_{,\alpha'}}\|_{L^2}^2 +$$

$$\|D_{\alpha'}^2 \frac{1}{Z_{,\alpha'}}\|_{L^2}^2 + \|\frac{1}{Z_{,\alpha'}} D_{\alpha'}^2 \bar{Z}_t\|_{\dot{H}^{1/2}}^2 + \|D_{\alpha'} \bar{Z}_t\|_{\dot{H}^{1/2}}^2 + \|\frac{1}{Z_{,\alpha'}}\|_{L^\infty}^2 \quad (10)$$

Then

$$E(t) \approx \mathcal{E}(t) \quad (11)$$

Difficulty with a singular weight:

Difficulties with singular weights:

- Place the singular weights in the right places in the nonlocal operators;
- The very low regularities involved;

$$(\partial_t + b\partial_{\alpha'})^2 \bar{Z}_t + iA\partial_{\alpha'}\bar{Z}_t = -iA_t\bar{Z}_{\alpha'}$$

$$A = \frac{A_1}{|Z_{\alpha'}|^2}$$

$$\frac{A_t}{A} = -\frac{\Im\{2[Z_t, \mathbb{H}]\overline{Z}_{tt,\alpha'} + 2[Z_{tt}, \mathbb{H}]\overline{Z}_{t,\alpha'} - [Z_t, Z_t; D_{\alpha'}Z_t]\}}{A_1}$$

Remarks:

- $$\frac{1}{Z_{,\alpha'}} = i\frac{\overline{Z}_{tt} - i}{A_1} \approx \overline{Z}_{tt} - i$$
- The self-similar solution has finite energy.
- In general, surfaces that have angled crests of interior angle $< \frac{\pi}{2}$, and the angle ν of the wave with the vertical wall $\nu < \frac{\pi}{4}$ have finite energy.
- Stokes wave of maximum height does not have finite energy.

Main Result

Theorem (A priori estimate, R. Kinsey & S. Wu)

There exists a polynomial $p = p(x)$ with universal coefficients, such that, for any solution of water wave equations with $E(t) < \infty$ for all $t \in [0, T]$,

$$\frac{d}{dt}E(t) \leq p(E(t)) \tag{12}$$

for all $t \in [0, T]$.

Theorem (local existence, S.Wu)

For any initial data satisfying $E(0) < \infty$, there exists $T > 0$, depending only on $E(0)$, such that the water wave equation is solvable for time $t \in [0, T]$, with $E(t) < \infty$ for $t \in [0, T]$.

Remark: for initial interface $z(\cdot, 0)$ satisfying $E(0) < \infty$ and with its angle function $\arg z(\cdot, 0)$ piecewise continuous, the interface $z(\cdot, t)$ will have its angle $\arg z(\cdot, t)$ piecewise continuous at later times $0 < t < T$. During this time the angles that the angled crests do not change.

–Observed by R. Kinsey,

–Rigorous proof by S. Agrawal

Theorem (blow-up criteria, S. Wu)

Given smooth data, there is a unique smooth solution exist for a positive time period $[0, T]$. *Let* T^* *be the maximum existence time for the smooth solution. Then either* $T^* = \infty$, *or* $T^* < \infty$, *but the interface* $z = z(\cdot, t)$ *becomes self-intersecting at time* T^*, *or* $\sup_{[0,T^*)} E(t) = \infty$.

Recall Wu (1997)

- Local wellposed was proved via the quasilinear equations in Riemann mapping variables

$$(\partial_t + b\partial_{\alpha'})^2 \bar{Z}_t + iA\partial_{\alpha'} \bar{Z}_t = -iA_t \bar{Z}_{\alpha'}$$

- This is an equation on the velocity Z_t. The interface induced by the solution may or may not be self-intersecting.
- Only non-self-intersecting interface gives rise to a solution of the Euler equation.
- The idea of solving for solutions, including self-intersecting interfaces, was later used in the work of Cordoba, Fefferman etc on splash, splat singularities.

Idea for the proof of the existence: build on the solutions in Wu (1997):

- mollify the initial data by the Poisson kernel.
- solve the "water wave system" for this initial data, the "solution" exists in Sobolev spaces for a time T depending only on $E(0)$.
- this "solution" may self-intersect, but it is well-defined in the Riemann mapping framework.
- pass to limit. show the limit satisfies the water wave system in the fluid domain in the classical sense.
- if the data is chord-arc, then the solution remains chord-arc for a time period depending only on $E(0)$ and the chord-arc constant.

Thank you very much for your attention!