Broadband forcing of turbulence

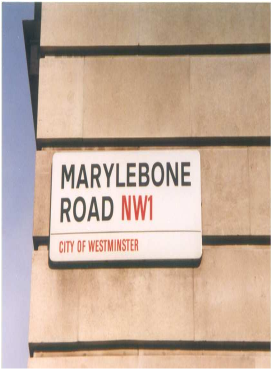
Bernard J. Geurts, Arek K. Kuczaj

Multiscale Modeling and Simulation (Twente)
Anisotropic Turbulence (Eindhoven)

IMS Turbulence Workshop
London, February 18-19, 2008

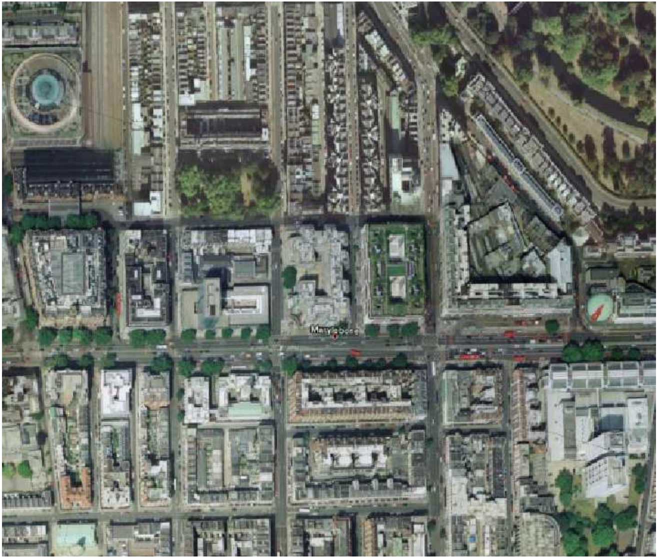
Underwater canopies

Urban dispersion



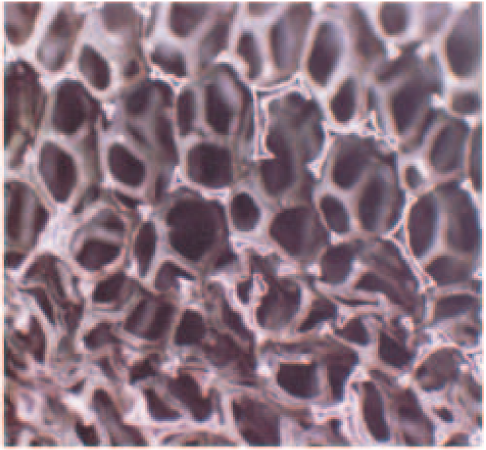
DAPPLE: Dispersion of Air Pollution and its Penetration into the Local Environment

Urban canopy



Rural dispersion - water management

Compact heat- and mass-transfer



Nickel foam - heat-pump applications

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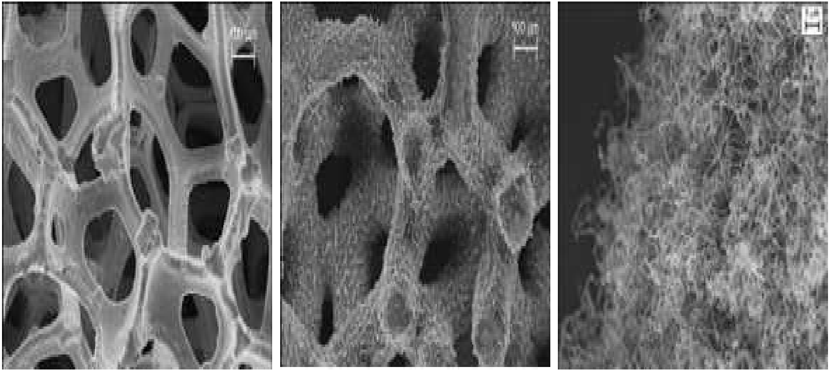
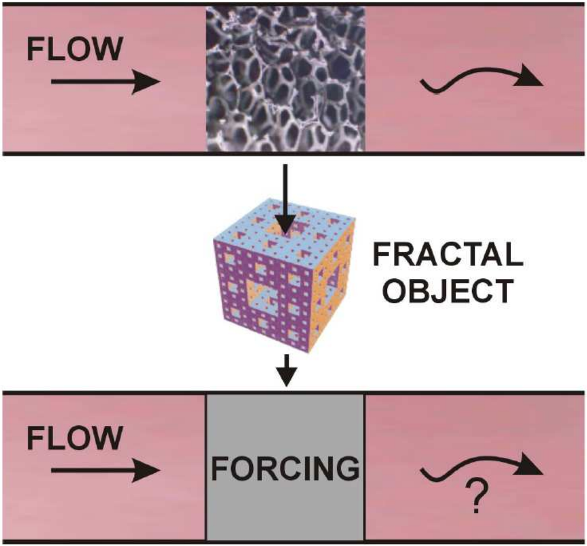


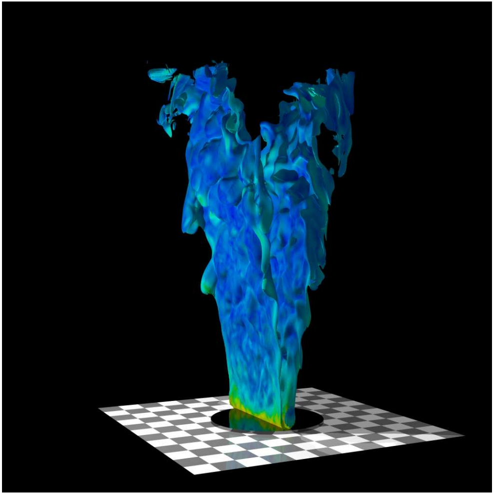
Coating with Carbon Nano Fibers - catalyst applications

Fractal modeling of complex objects?



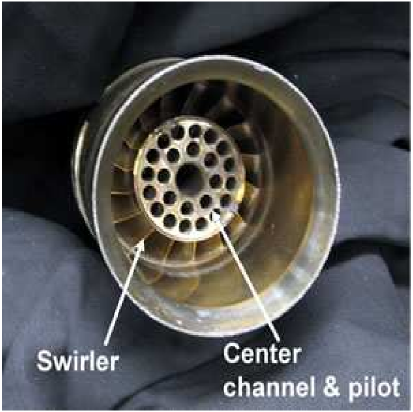
TU/e

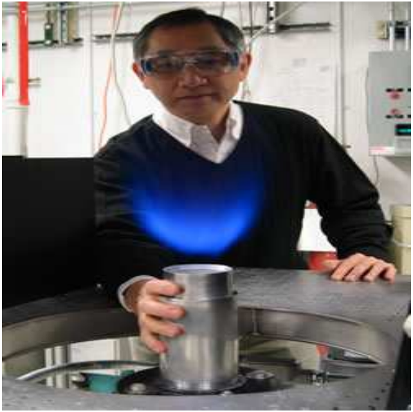
Controlling scales in flames



Effect of an upstream rod in flame

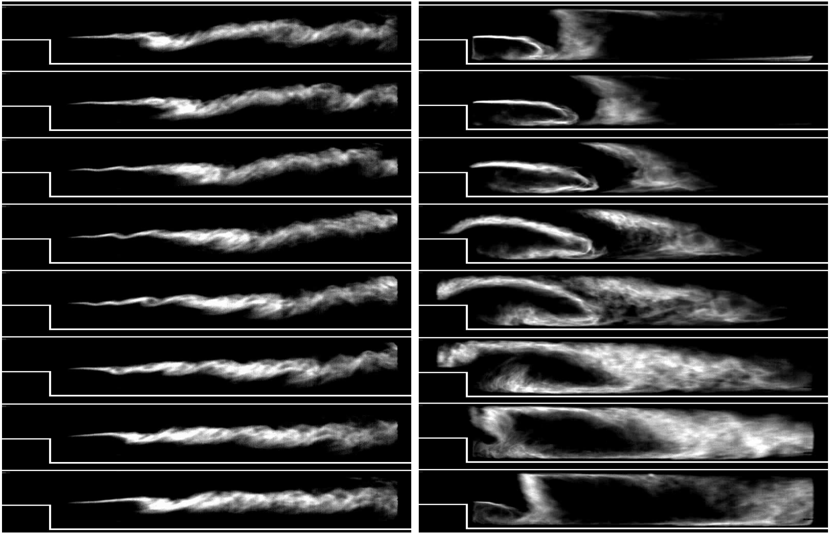
Swirl control of lean combustion





Adding swirl stabilizes flame but hinders mixing

Enhanced syngas combustion



Intensified combustion following upstream flow instability

Will

- present broadband forcing methodology
- obtain controlled non-Kolmogorov turbulence
- consider effects on mixing rate
- investigate responsiveness to time-dependent forcing
- present problem of relating forcing to actual (fractal) object

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Outline

1. Forcing at various scales
2. Mixing in manipulated turbulence
3. Optimal forcing?
4. Connections to real objects
5. Concluding remarks

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Forcing incompressible flow

Physical space: $\nabla \cdot \mathbf{v} = 0$

$$\frac{\partial \mathbf{v}}{\partial t} + \left(\mathbf{v} \cdot \nabla\right)\mathbf{v} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{v} + \mathbf{f}$$

Spectral space: put $\mathbf{F} = \mathcal{F}(\mathbf{f})$ and assume $\mathbf{k} \cdot \mathbf{F} = 0$. Then

$$\mathbf{v}(\mathbf{x}, t) = \sum_{\mathbf{k}} \mathbf{u}(\mathbf{k}, t) e^{\imath \mathbf{k} \cdot \mathbf{x}}$$

with

$$\left(\frac{\partial}{\partial t} + \nu k^2\right) \mathbf{u}(\mathbf{k}, t) = \mathbf{D}\, \mathbf{W}(\mathbf{k}, t) + \mathbf{F}(\mathbf{k}, t)$$

where

$$D_{\alpha\beta} = \delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{k^2} \quad ; \quad \mathbf{W}(\mathbf{k}, t) = \mathcal{F}\Big(\mathbf{v}(\mathbf{x}, t) \times \omega(\mathbf{x}, t)\Big)$$

Pseudo-spectral treatment, FFTW, de-aliased, ...

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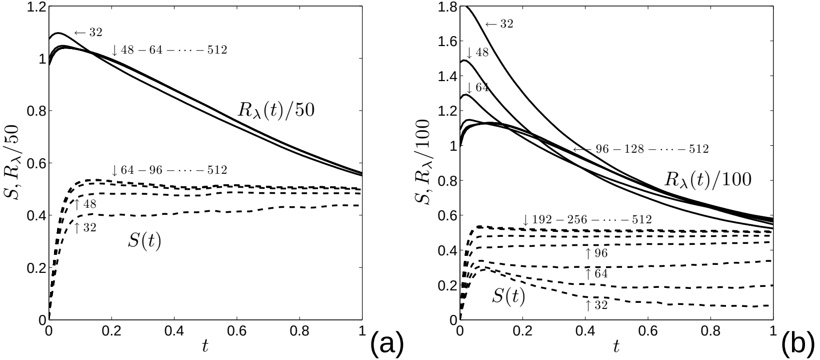
Convergence for decaying turbulence



R_λ and skewness S at initial $R_\lambda = 50$ (a) and $R_\lambda = 100$ (b)

R_λ/N^3	32^3	48^3	64^3	96^3	128^3	192^3	256^3	384^3	512^3
50	0.56	0.83	1.11	1.67	2.22	3.34	4.45	6.67	8.90
100	0.20	0.29	0.39	0.59	0.79	1.18	1.57	2.36	3.15

$k_{max}\eta$ at different N

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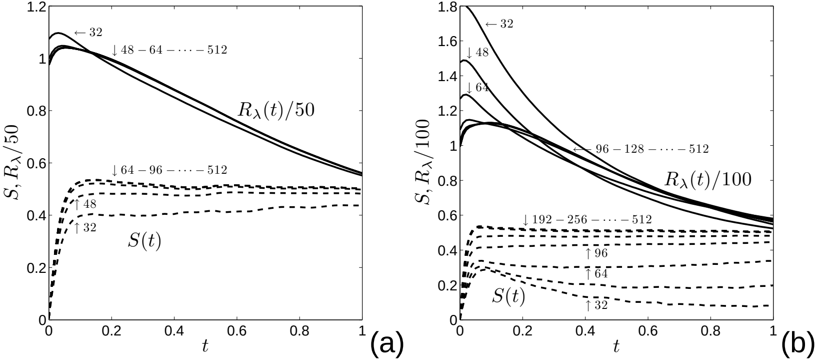

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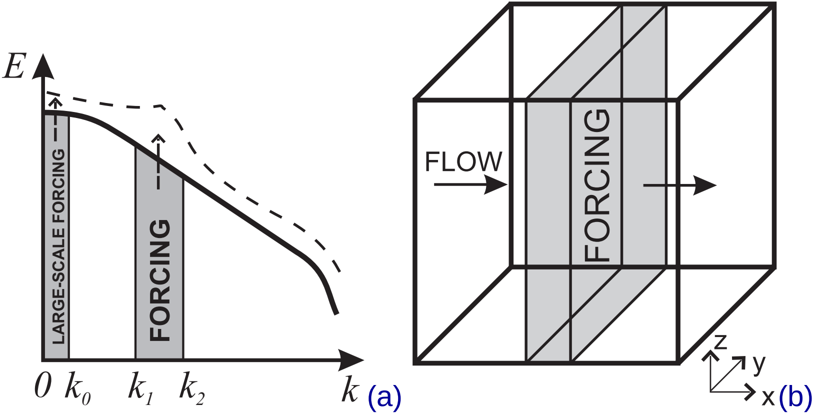
Forcing: spectral and physical localization



a: Two-band forcing in spectral space

b: Forcing in a slab in physical space - spectral convolution

Energy and forcing

> Evolution of Fourier coefficients

$$\left(\frac{\partial}{\partial t} + \nu k^2\right) u_\alpha(\mathbf{k},t) = \Psi_\alpha(\mathbf{k},t) + F_\alpha(\mathbf{k},t)$$

where $\Psi_\alpha(\mathbf{k},t) = D_{\alpha\beta} W_\beta(\mathbf{k},t)$

> Energy evolution: $E(\mathbf{k},t) = \frac{1}{2}\left|\mathbf{u}(\mathbf{k},t)\right|^2$

$$\frac{\partial E(\mathbf{k},t)}{\partial t} = -\varepsilon(\mathbf{k},t) + T(\mathbf{k},t) + T_F(\mathbf{k},t)$$

- dissipation $\varepsilon(\mathbf{k},t) = 2\nu k^2 E(\mathbf{k},t)$
- transfer $T(\mathbf{k},t) = u_\alpha^*(\mathbf{k},t)\Psi_\alpha(\mathbf{k},t)$
- forcing $T_F(\mathbf{k},t) = u_\alpha^*(\mathbf{k},t)F_\alpha(\mathbf{k},t)$

Various forcing strategies possible - consider constant energy in (some) modes (‘A’) and constant energy input-rate (‘B’)

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Basic forcing of type 'A'

Choose to have $\partial_t u_\alpha = 0$, i.e., $\partial_t E(\mathbf{k}, t) = 0$ for forced modes

Obtain forcing:

$$A1: \quad F_\alpha(\mathbf{k}, t) = \nu k^2 u_\alpha(\mathbf{k}, t) - \Psi_\alpha(\mathbf{k}, t)$$

Extensions keeping $|\mathbf{u}(\mathbf{k}, t)|$ constant (Chasnov)

$$F_\alpha(\mathbf{k}, t) = (\varepsilon(\mathbf{k}, t) - T(\mathbf{k}, t)) \frac{u_\alpha(\mathbf{k}, t)}{2E(\mathbf{k}, t)}$$

or shell-averaged version (Kerr)
Or average over all modes: (and assign to P forced modes)

$$A2: \quad F_\alpha(\mathbf{k}, t) = \frac{\widehat{\varepsilon}(t)}{P} \frac{u_\alpha(\mathbf{k}, t)}{2E(\mathbf{k}, t)}$$

yielding constant energy for entire system

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Constant energy input rate: ‘B’

Energy input rate ε_w fixed per forced mode:

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Multiscale stirrer: (Mazzi, Vassilicos)

$$B2: \quad F_\alpha(\mathbf{k},t) = \frac{\varepsilon_w k^\beta}{\sum_{\mathbf{k}\in\mathbb{K}}\sqrt{2E(\mathbf{k},t)}k^\beta}\, e_\alpha(\mathbf{k},t)$$

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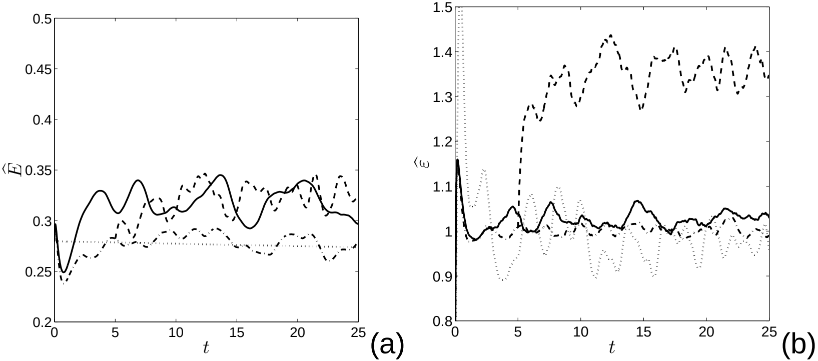
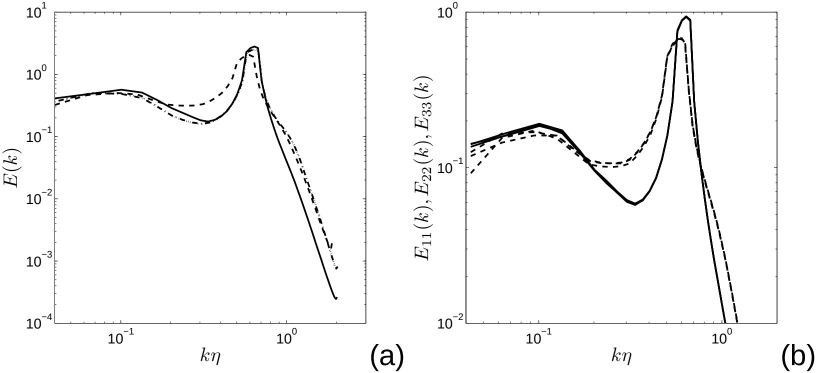
Two-band forcing



Kinetic energy $\widehat{E}$ (a) and energy-dissipation-rate $\widehat{\varepsilon}$ (b)

A1 (dashed), A2 (dotted), B1 (dash-dotted), B2 (solid)

Two-band forcing: compensated spectra

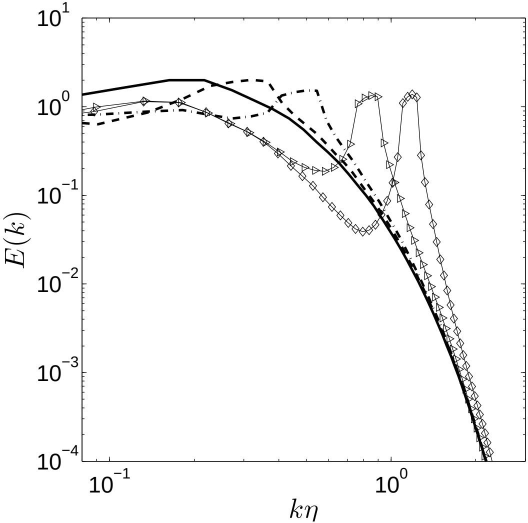


two-band forced turbulence: $k \leq 3\pi$ and $33\pi < k \leq 41\pi$

(a) A1 (dashed), A2 (dotted), B1 (dash-dotted), B2 (solid)

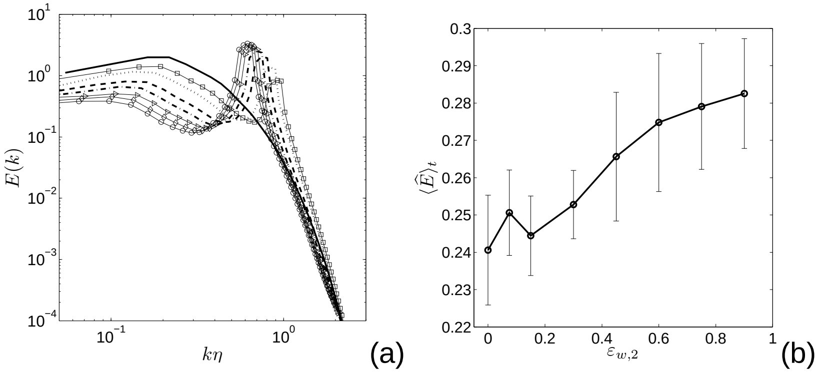
(b) Co-spectra E_{11}, E_{22}, E_{33} for A1 (dashed) and B2 (solid)

Peak where you want: B2



Equal forcing per band: $\varepsilon_{w,1} = \varepsilon_{w,2} = 0.15$

Peak with desired strength: B2



(a) large-scale forcing $\varepsilon_{w,1} = 0.15$ in $k \leq 3\pi$: second band $33\pi < k \leq 41\pi$: $\varepsilon_{w,2} = 0.075, 0.15, 0.30, \ldots, 0.90$

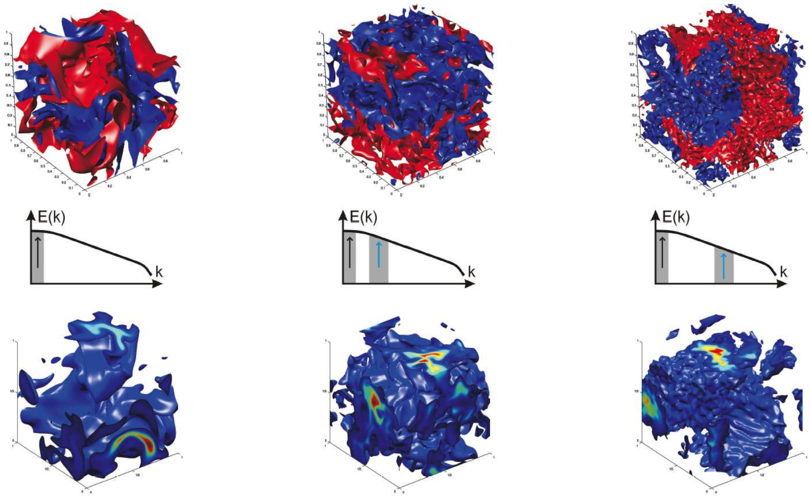
(b) Corresponding time-averaged total kinetic energy

Forcing removes energy from large scales - nonlocality

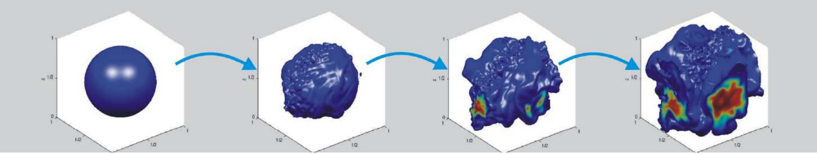
Outline

Fractal stirring at various scales

Controlled mixing in two-band forcing



Scalar mixing: area and wrinkling



Geometric properties level-set: where $c(\mathbf{x}, t) = a$

$$I_g(a,t) = \int_{S(a,t)} dA \; g(\mathbf{x}, t)$$

- $g(\mathbf{x}, t) = 1$: area A
- $g(\mathbf{x}, t) = |\nabla \cdot \mathbf{n}(\mathbf{x}, \mathbf{t})|$: wrinkling W

Instantaneous and cumulative:

$$\vartheta_A(a,t) = A(a,t)/A(a,0) \quad ; \quad \vartheta_W(a,t) = W(a,t)/W(a,0)$$

$$\zeta_A(a,t) = \int_0^t \vartheta_A(a,\tau)d\tau \quad ; \quad \zeta_W(a,t) = \int_0^t \vartheta_W(a,\tau)d\tau$$

Distinguish: rate and maxima (ϑ) and total effect over time (ζ)

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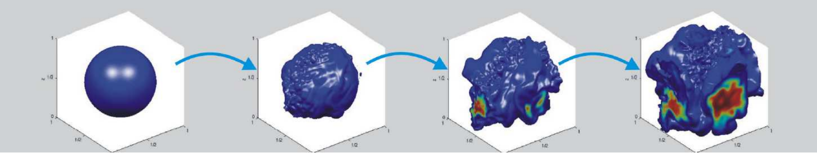

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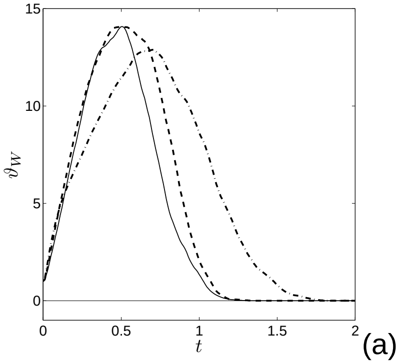
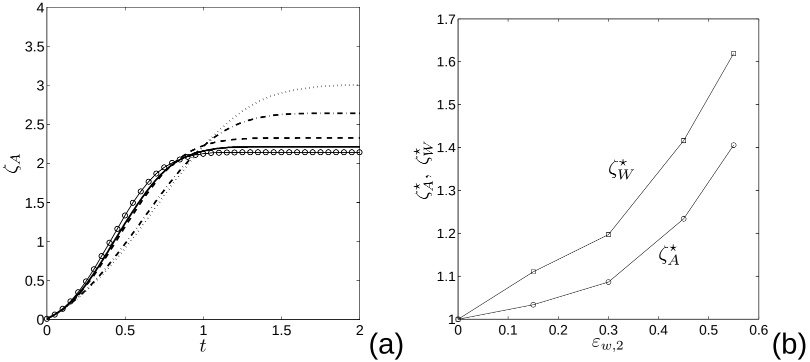
Evolution of wrinkling ϑ_W and ζ_W



Comparing: forcing

- $\mathbb{K}_{1,1}$ at $\varepsilon_W = 0.60$ (solid)
- $\mathbb{K}_{1,1}$ at $\varepsilon_W = 0.15$ and $\mathbb{K}_{5,8}$ at $\varepsilon_{W,2} = 0.45$ (dashed)
- $\mathbb{K}_{1,1}$ at $\varepsilon_W = 0.15$ and $\mathbb{K}_{13,16}$ at $\varepsilon_{W,2} = 0.45$ (dash-dotted)

Mixing: value for money



- Forcing $\mathbb{K}_{1,1} - \mathbb{K}_{13,16}$ at (0.60 – 0.00) (∘), (0.45 – 0.15) (solid), (0.30 – 0.30) (dash), (0.15 – 0.45) (dot-dash), (0.05 – 0.55) (dot)
- surface-area (a) and wrinkling $\zeta_W^\star$ at $t = 2$ (b)

Outline

Preferred frequency for turbulence agitation?

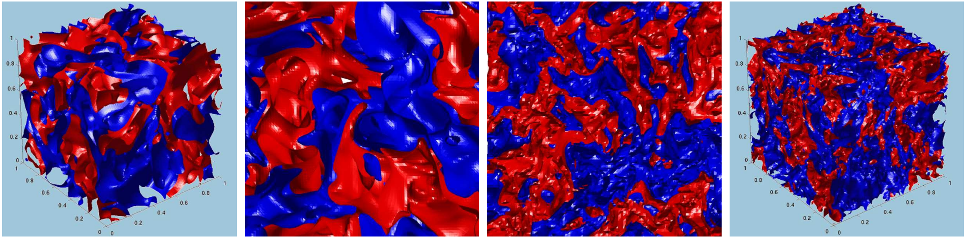
So far: forcing at various spatial scales

What about time-modulation of forcing?

Consider forcing at:

(1) large-scales only

(2) various scales simultaneously



Modulated Forcing

Time-modulation of forcing (B1):

$$F_\alpha(\mathbf{k},t) = \left[\frac{\varepsilon_W}{P}\,\frac{u_\alpha(\mathbf{k},t)}{2E(\mathbf{k},t)}\right]\,\Big(1 + A\sin(\omega t)\Big)$$

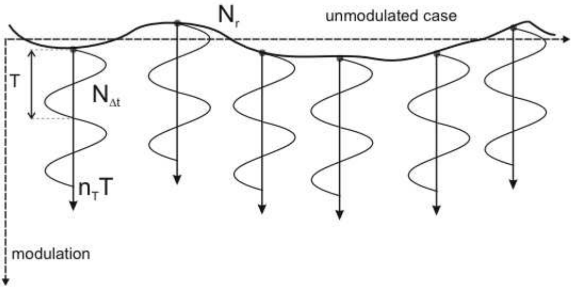
Expect:

- $\omega \gg 1$: modulation too rapid: no/small effect
- $\omega \ll 1$: modulation quasi-stationary: no/small effect

Q1: optimal modulation frequency/frequencies?

Q2: increased turbulence/transport/mixing?

Ensemble of forced simulations



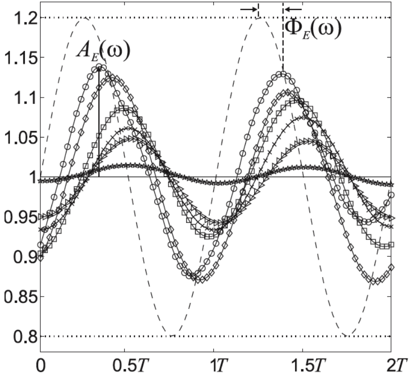
Registration total kinetic energy:

- start: j-th initial condition, N_r realizations
- forced - no modulation: $E_j^{(0)}(t)$
- forced - modulation: $E_j(t,\omega)$

Extract Amplitude and Phase

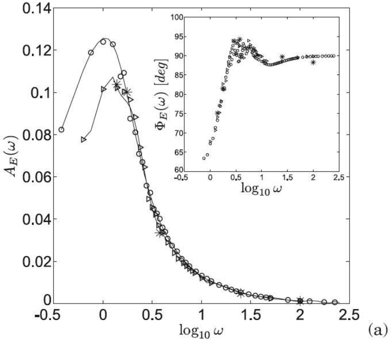
Averaging over N_r realizations:

$$\langle E(t,\omega)\rangle = \frac{1}{N_r}\sum_{i=1}^{N_r} E_j(t,\omega) = a(\omega) + A(\omega)\sin\left(\widehat{\omega}(t+\Phi(\omega))\right)$$



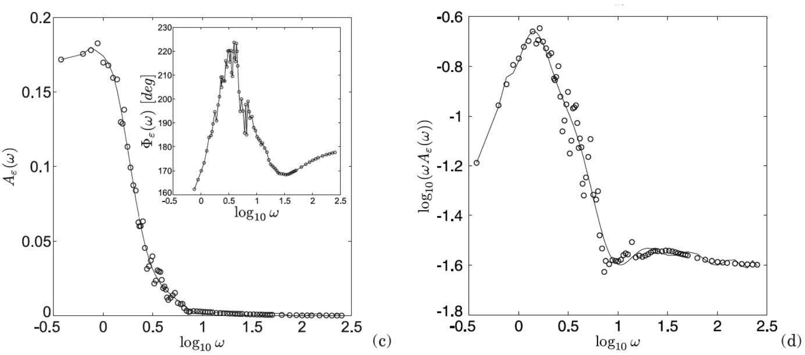
Amplitude response and phase-shift

Response maxima: energy



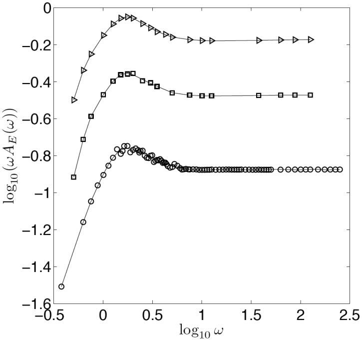
- $R_\lambda = 50$: $\circ$, and $R_\lambda = 100$: $\triangle$
- Phase-shift: $\omega \gg 1$ then $\rightarrow$ 90-degrees
- Compensated spectrum: ω^{-1} decay

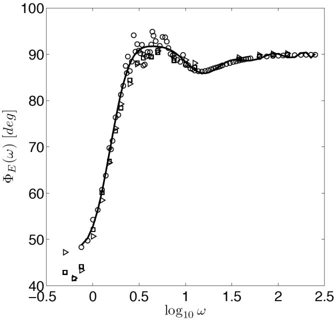
Response maxima: dissipation



- Phase-shift: $\omega \gg 1$ then $\rightarrow$ 180-degrees

Effect of amplitude of modulation

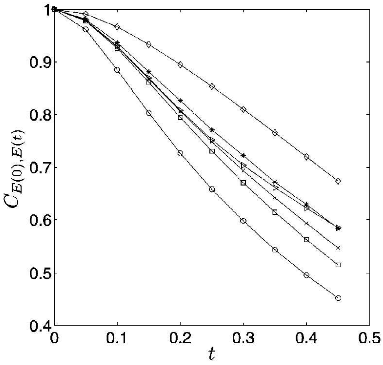




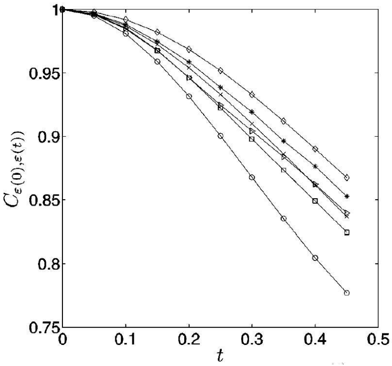
Modulation depth: $A = 1/5$ ($\circ$), $A = 1/2$ ($\square$), $A = 1$ ($\triangle$)

Response maxima and correlations?

Kinetic energy

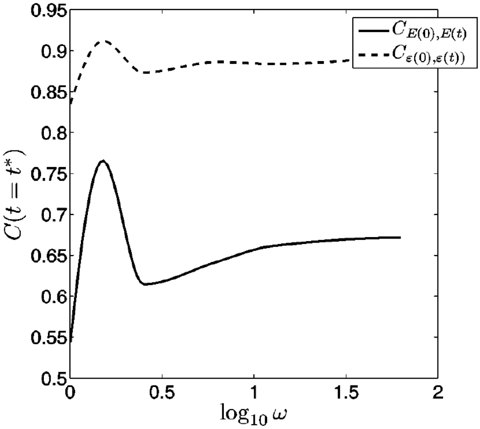


Energy-dissipation rate



$$C_{E(0),E(t)}(\omega) = \frac{\langle E(0)E(t)\rangle}{\langle E(0)^2\rangle^{1/2}\langle E(t)^2\rangle^{1/2}}$$

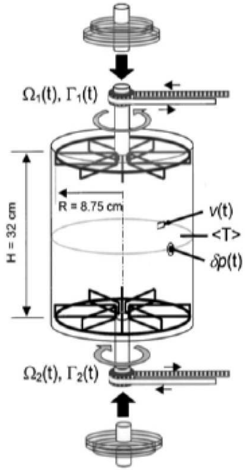
Response maxima and correlations?



Maximal correlation at ω at which response maximum

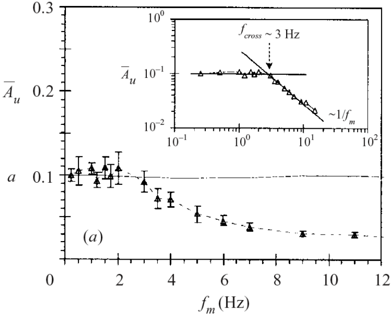
Here: $t^* = 0.3$

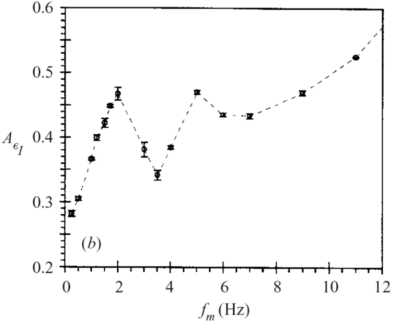
Experimental 'similarities': washing machine



Cadot-Titon-Bonn (JFM 485, 2003)

Experimental 'similarities': washing machine

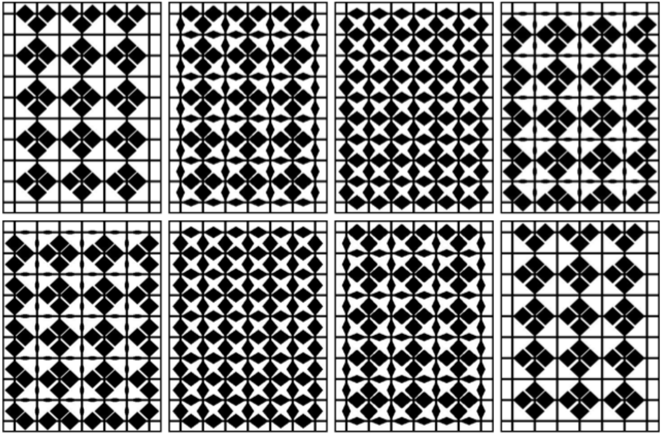




Velocity fluctuations (left) and power-input (right)

Possible Connections with Experiments?

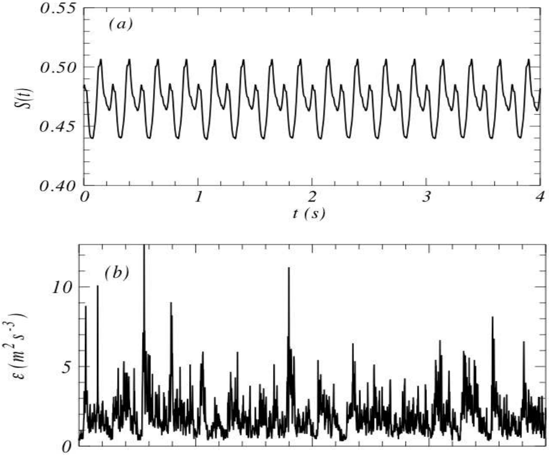
Periodic active grid mode: Tipton - van de Water



Grid can be cycled at different frequencies

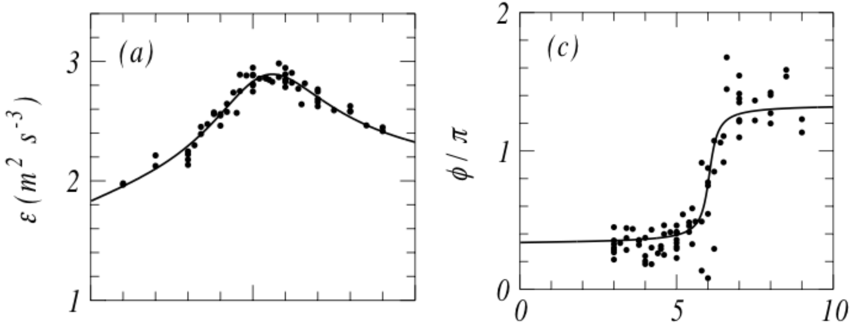
Dissipation rate in modulated turbulence

Grid solidity and dissipation rate:



Low-pass filtering of the dissipation-rate

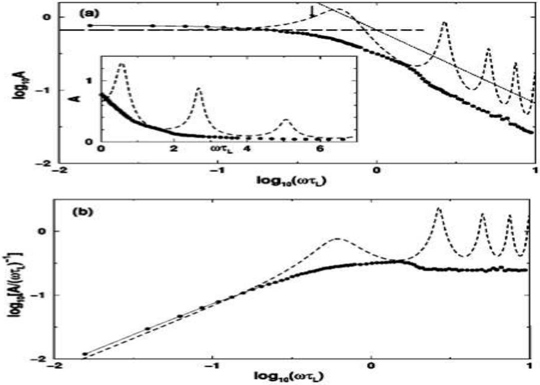
Frequency dependence



Resonant dissipation - phase shift of 180 degrees

Mean field and GOY?

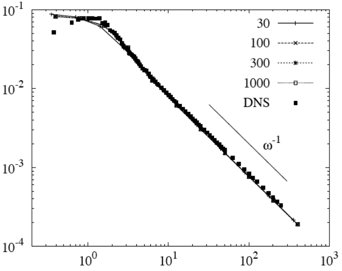
Heydt-Grossman-Lohse



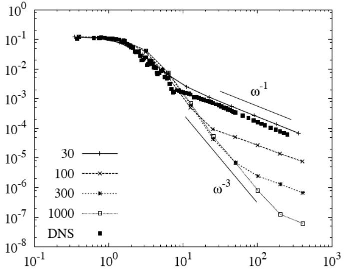
- Dashed: mean-field, Dots: GOY simulation
- GOY and REWA simulations show only small effect
- dissimilar to numerical NS experiments

Two point closure

Bos-Rubinstein



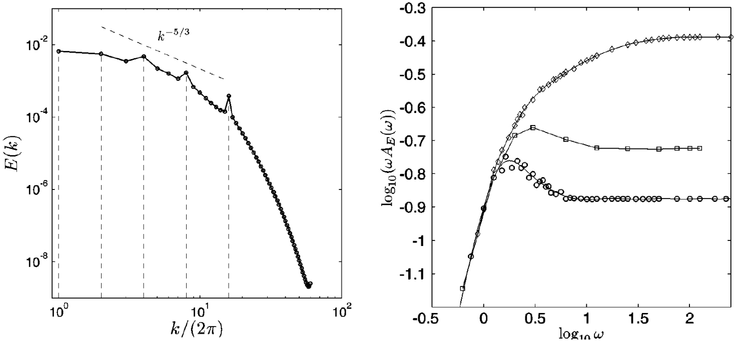
(a)



(b)

Energy (a) and dissipation (b): two-point closure approach compares closely to DNS

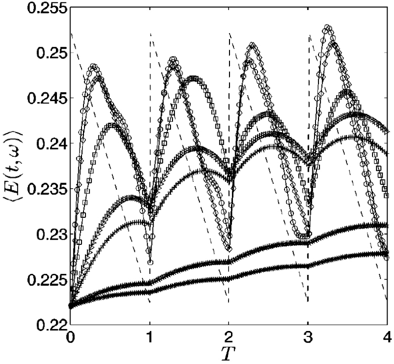
Multiscale forcing

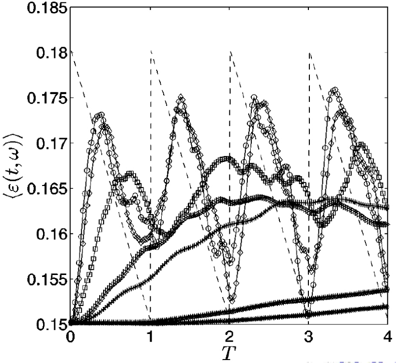


Response maxima pronounced when large scales forced

More pronounced as *Re* lower

Complex forcing strategies

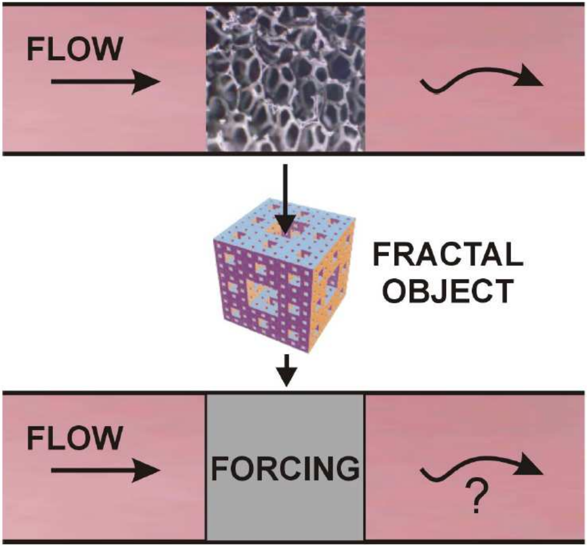




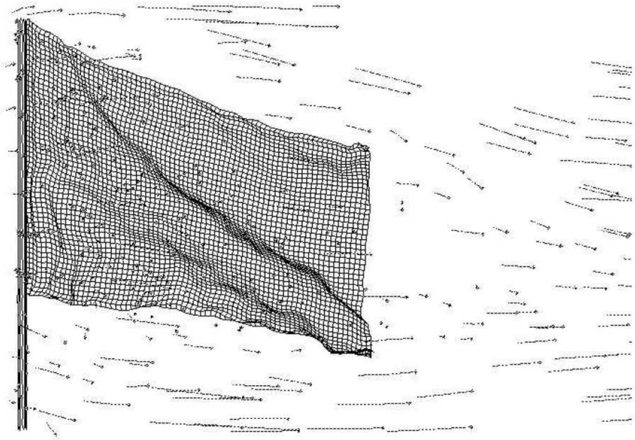
Response to saw-tooth forcing

Outline

Fractal modeling of complex objects?



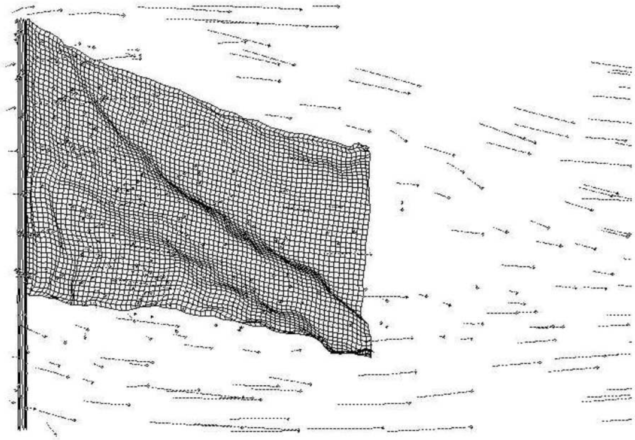
IBM - basics



Peskin, c.s.

- Compute on simple grid - cut out object
- fast solvers - complex geometries

IBM - basics



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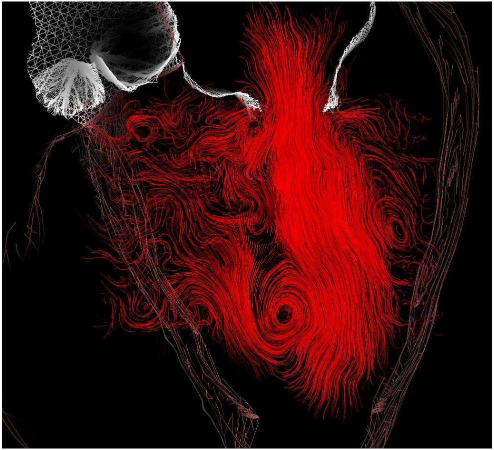
IBM in life-sciences



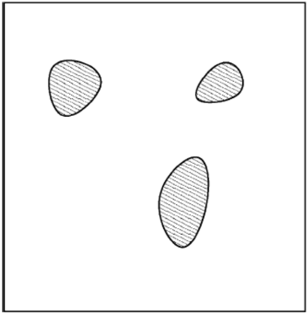
Famous application: flow in realistic heart

IBM - volume penalization

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla p - \frac{1}{Re}\Delta \mathbf{u} + \frac{1}{\epsilon} H \mathbf{u} = 0$$

Indicator function:

$$H = \begin{cases} 1 & \mathbf{x} \in \Omega_s \\ 0 & \mathbf{x} \in \Omega_f \end{cases}$$



How to relate forcing to IBM?

Case studies:

- bottom-up: optimize forcing to comply with simulated flow?
- top-down: relate ‘objects’ to ‘local fractal dimension’?
- ...
- can lack of detailed resolution be ‘modeled away’ at all?
- how much geometric detail is needed?
- can two-point closure provide guidance?
- ...

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Outline

1. Forcing at various scales
2. Mixing in manipulated turbulence
3. Optimal forcing?
4. Connections to real objects
5. **Concluding remarks**

Summary

- considered effect of broadband forcing on turbulent flow
- quantitative and qualitative changes of cascading possible
- controlling mixing rate and mixing 'completeness'
- 'receptivity' to agitation probed with time-modulated forcing
- response maxima, correlations
- connect complex geometry to specific forcing?

Thanks: NCF

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