Broadband forcing of turbulence

Bernard J. Geurts, Arek K. Kuczaj

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

IMS Turbulence Workshop
Underwater canopies

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**Urban dispersion**

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

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Rural dispersion - water management

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Compact heat- and mass-transfer

Nickel foam - heat-pump applications

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Compact heat- and mass-transfer

Coating with Carbon Nano Fibers - catalyst applications
Fractal modeling of complex objects?
Controlling scales in flames

Effect of an upstream rod in flame

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Swirl control of lean combustion

Adding swirl stabilizes flame but hinders mixing

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Enhanced syngas combustion

Intensified combustion following upstream flow instability

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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

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

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

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

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

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Pseudo-spectral treatment, FFTW, de-aliased, ...
**Convergence for decaying turbulence**

**R_λ** and skewness **S** at initial **R_λ = 50** (a) and **R_λ = 100** (b)

<table>
<thead>
<tr>
<th>R_λ/N³</th>
<th>32³</th>
<th>48³</th>
<th>64³</th>
<th>96³</th>
<th>128³</th>
<th>192³</th>
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<td>50</td>
<td>0.56</td>
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<td>1.67</td>
<td>2.22</td>
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<td>0.79</td>
<td>1.18</td>
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**k_{max}η** at different **N**
Convergence for decaying turbulence

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

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$k_{\text{max}}\eta$ at different $N$
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

\[ \left( \frac{\partial}{\partial t} + \nu k^2 \right) u_\alpha(k, t) = \psi_\alpha(k, t) + F_\alpha(k, t) \]

where \( \psi_\alpha(k, t) = D_{\alpha\beta} W_\beta(k, t) \)

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

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

- dissipation \( \varepsilon(k, t) = 2\nu k^2 E(k, t) \)
- transfer \( T(k, t) = u^*_\alpha(k, t) \psi_\alpha(k, t) \)
- forcing \( T_F(k, t) = u^*_\alpha(k, t) F_\alpha(k, t) \)

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

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

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

Obtain forcing:

$$A1 : \quad F_\alpha(k, t) = \nu k^2 u_\alpha(k, t) - \psi_\alpha(k, t)$$

Extensions keeping $|u(k, t)|$ constant (Chasnov)

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

or shell-averaged version (Kerr)

Or average over all modes: (and assign to $P$ forced modes)

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

yielding constant energy for entire system
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yielding constant energy for entire system
Constant energy input rate: ‘B’

Energy input rate $\varepsilon_w$ fixed per forced mode:

\[ B1 : \quad F_\alpha(k, t) = \frac{\varepsilon_w u_\alpha(k, t)}{P \frac{2E(k, t)}{k^\beta}} \]

Multiscale stirrer: (Mazzi, Vassilicos)

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

where $\mathbb{K}$ is set of forced modes and

\[ e(k, t) = \frac{u(k, t)}{|u(k, t)|} + \frac{k \times u(k, t)}{|k||u(k, t)|} \]

- complexity of stirrer ‘contained’ in exponent $\beta(=3/5)$, related to fractal dimension $D_f = \beta + 2$
Constant energy input rate: ‘B’

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Two-band forcing

Kinetic energy $\hat{E}$ (a) and energy-dissipation-rate $\hat{\varepsilon}$ (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: $\varepsilon_{w,1} = \varepsilon_{w,2} = 0.15$
(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

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2. Mixing in manipulated turbulence
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4. Connections to real objects
5. Concluding remarks
Fractal stirring at various scales
Controlled mixing in two-band forcing

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Scalar mixing: area and wrinkling

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

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

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

Instantaneous and cumulative:

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

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

Distinguish: rate and maxima ($\vartheta$) and total effect over time ($\zeta$)
Scalar mixing: area and wrinkling

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

$$l_g(a, t) = \int_{S(a,t)} dA \ g(x, t)$$

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Instantaneous and cumulative:

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Distinguish: rate and maxima ($\vartheta$) and total effect over time ($\zeta$)
Evolution of wrinkling $\vartheta_W$ and $\zeta_W$

Comparing: forcing
- $K_{1,1}$ at $\varepsilon_w = 0.60$ (solid)
- $K_{1,1}$ at $\varepsilon_w = 0.15$ and $K_{5,8}$ at $\varepsilon_w,2 = 0.45$ (dashed)
- $K_{1,1}$ at $\varepsilon_w = 0.15$ and $K_{13,16}$ at $\varepsilon_w,2 = 0.45$ (dash-dotted)
Mixing: value for money

- Forcing $K_{1,1} - K_{13,16}$ 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 $\zeta^{*}_W$ at $t = 2$ (b)

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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):

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

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:

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

- $R_\lambda = 50$: ○, and $R_\lambda = 100$: △
- Phase-shift: $\omega \gg 1$ then $\rightarrow$ 90-degrees
- Compensated spectrum: $\omega^{-1}$ decay
Response maxima: dissipation

- Phase-shift: $\omega \gg 1$ then $\rightarrow 180$-degrees
Effect of amplitude of modulation

Modulation depth: $A = 1/5$ (○), $A = 1/2$ (□), $A = 1$ (△)
Response maxima and correlations?

Kinetic energy

Energy-dissipation rate

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

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Response maxima and correlations?

Maximal correlation at $\omega$ at which response maximum
Here: $t^* = 0.3$
Experimental ‘similarities’: washing machine

Cadot-Titon-Bonn (JFM 485, 2003)

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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

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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

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Two point closure

Bos-Rubinstein

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

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Multiscale forcing

Response maxima pronounced when large scales forced
More pronounced as $Re$ lower

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Complex forcing strategies

Response to saw-tooth forcing
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Fractal modeling of complex objects?
IBM - basics

Peskin, c.s.
- Compute on simple grid - cut out object
- Fast solvers - complex geometries

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IBM in life-sciences

Famous application: flow in realistic heart

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IBM - volume penalization

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

Indicator function:

\[ H = \begin{cases} 
1 & \text{if } x \in \Omega_s \\
0 & \text{if } x \in \Omega_f 
\end{cases} \]
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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- 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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