1. Influence of outer large-scale structures on near wall small-scale structures
2. DBD Plasma Actuators for drag reduction in wall-bounded turbulent flows

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5. Conclusion
The effect of the outer LS structures 'super-streaks' in the log-law region on the inner (near-wall) turbulent fluctuations:

- **Footprinting effect:** LS motions interact with the corresponding large translational fluctuations near the wall.
  \[ \text{LS (outer)} \rightarrow \text{LS (inner)} \]

- **Modulation effect:** intensity of the large-scales causes an amplification or attenuation of the intensity of the small-scales.
  1. **Two-point Analysis:**
     \[ \text{LS (outer)} \rightarrow \text{SS (inner)} \]
     This is ideal method to investigate the amplitude modulation.
  2. **Single-point Analysis:** with the assumption of the footprint at inner point of the superstructure-type events is sufficient to provide a reasonable estimate of the degree of amplitude modulation.
     \[ \text{LS (inner)} \rightarrow \text{SS (inner)} \]

**Methods used are:**
- Filtering and Hilbert Transform
- 1-D EMD (Empirical Mode Decomposition)

**Database used is:**
- Chalmers data, the domain size is \( 2\pi \delta \times 2\delta \times \pi \delta \) with grid sizes \( 258 \times 98 \times 258 \), in the streamwise, wall-normal and spanwise directions, Reynolds number is \( Re_\tau = 550 \).
  Temporal signal of streamwise velocity fluctuations over a specific wall-normal location are obtained.
Mode Decomposition by EMD: For example

\[ X(t) = 4\cos(10t) + 2\cos(t) + 3 \]

signal has components, 3, 2\( \cos(t) \) and 4\( \cos(10t) \).

*Of course in real applications we do not know the components but have only a complex data.*

If we apply EMD to the signal \( X(t) \) we get IMFs (Intrinsic Mode Functions). For this example IMFs are 2\( \cos(t) \) and 4\( \cos(10t) \). We get 3 as a residual, due to IMF extracting process ends when once reached a monoton signal.

For this example:
- IMF 1 = 4\( \cos(10t) \) (Highest frequency component is extracted first).
- IMF 2 = 2\( \cos(t) \) (Second highest frequency component).
- IMF 3 (or residual if we cut the process at 2nd IMF) = 3.
An Example:

\[ x(t) = 4\cos(10t) + 2\cos(t) + 3 \]

Fig. 1 Algorithm of 1-D EMD by Hilbert-Huang Transformation.

Fig. 2 Original Signal, \( x(t) \).

Fig. 3 IMFs obtained.
ICL spatial data (streamwise-spanwise snapshots) is used. Domain size: $4\pi h \times 2h \times 2\pi h$, Grid size: $1056 \times 528 \times 1056$, in the streamwise, wall-normal and spanwise directions. L. Agostini & M. A. Leschziner, Phys. Fluids 2014

**Fig.4** Inner data, $y^+ \approx 15$. Raw data, LS obtained by EMD, LS obtained by filtering given respectively from left.

**Fig.5** Outer data, $y^+ \approx 200$. Raw data, LS obtained by EMD, LS obtained by filtering given respectively from left.
Footprinting

ICL spatial data (streamwise-spanwise snapshots) is used.

Fig. 6 Outer data from $y^+ \approx 200$, and inner data from $y^+ \approx 15$.

Footprints for four randomly chosen locations, $z^+ \approx 1600$, $z^+ \approx 3200$, $z^+ \approx 4800$ and $z^+ \approx 6400$, respectively.
Amplitude Modulation Analysis Procedure by Filtering and Hilbert Transformation

- **Raw signals, \( u_i^+ \) from inner, and \( u_o^+ \) from outer peak.**

- **Filtering to \( u_i^+ \) (\( \lambda_i/\delta < \text{cutoff wavelength} \))**

- **Filtering to \( u_o^+ \) (\( \lambda_o/\delta > \text{cutoff wavelength} \))**

- **Small-scales, \( u_{i,S}^+ \)**

  - **SS: Amplitude-modulated signal**

  - **Hilbert T.**

  - **Envelope \( E(u_{i,S}^+) \)**

  - **Modulating Wave**

  - **Filtering (\( \lambda_i/\delta > \text{cutoff wavelength} \))**

- **Large-scales, \( u_{o,L}^+ \)**

- **Degree of amp. modulation:**

  \[
  \begin{align*}
  R &= \frac{\frac{\omega_i^+ E_i(u_{i,S}^+)}{\sqrt{u_i^+ E_{i}(u_{i,S}^+)}}}{\frac{\omega_o^+ E_o(u_{o,L}^+)}{\sqrt{u_o^+ E_{o}(u_{o,L}^+)}}} \\
  &= \frac{\omega_i^+ E_i(u_{i,S}^+)}{\omega_o^+ E_o(u_{o,L}^+)}
  \end{align*}
  \]

**Fig.7** Decoupling procedure by filtering and Hilbert Transform. (Mathis et. al., JFM 2009)
Temporal signal over a specific wall-normal location is used. In this study subscripts, 'i', 'o', 'S', 'L', represents the 'inner', 'outer', 'small-scale' and 'large-scale'. For instance, \( u_i^+, S \) and \( u_i^+, L \) represents the small and large-scales for the inner peak location \( (y^+ = 15) \), respectively.

Fig.8 Contours of pre-multiplied energy spectra, \( k_x \Phi_{uu}(k_z)/u_+ \).

Fig.9 Data from \( y^+ = 150 \) and \( y^+ = 10 \), \( Re_\tau = 550 \).

Fig.10 Comparation of filtered signals, Mathis et al. method.
Amplitude Modulation Analysis by Filtering applied to ICL data

ICL spatial data (streamwise-spanwise snapshots) is used. Two-point analysis.

Fig.11 Outer data from $y^+ \approx 200$, and inner data from $y^+ \approx 15$. Locations are, $z^+ \approx 800$, $z^+ \approx 1600$ and $z^+ \approx 4800$, respectively.

Amplitude modulation analysis is here applied to the instantaneous streamwise fluctuating velocity signals at three different $z^+$ locations.

- $E_L(u^+_{i,S})$: Envelope of inner-small scales,
- $E(u^+_{o,L})$: outer large-scale structures.
Amplitude Modulation Analysis by Filtering applied to ICL data

Footprinting enables to modulation analysis by inner data (one-point analysis)

The so called one-point analysis which estimates the degree of amplitude modulation should give similar results as the two-point analysis. The idea is that LS motions from the outer layer affects the SS inner structures via footprinting on the LS inner structures.

Fig.12 Amplitude modulation analysis could be performed by both outer or inner LS data.
Amplitude Modulation Analysis by Filtering applied to ICL data

ICL spatial data (streamwise-spanwise snapshots) is used. One-point analysis.

**Fig. 13** Inner data is used from $y^+ \approx 15$. Locations are, $z^+ \approx 800$, $z^+ \approx 1600$ and $z^+ \approx 4800$, respectively.

Same $z^+$ locations with two-point analysis. Correlation is weaker compared to the two-point analysis, but still exist due to footprinting.

- $E_L (u_i^+, S)$: Envelope of inner-small scales,
- $E(u_{i,L}^+)$: inner large-scale structures.
Existing and Suggested Methods for Amplitude Modulation Analysis

1. Large-small scale Interaction
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- **Fig. 14**: Decoupling procedure based on filtering. (Mathis et. al., JFM 2009)

- **Fig. 15**: Decoupling procedure suggested based on EMD.
Application of the two Methods

Two-point Analysis, Left and right hand sides.

Fig.16 Left hand side of the methods.

Fig.17 Right hand side of the methods.
Application of the two Methods

Two-point Analysis, modulation results.

Fig.18 Analysis results by filtering based method.

Fig.19 Analysis results by EMD based method.

$R = 0.26$, and $R = 0.29$ for the correlation coefficient for the Mathis et al. and present methods, respectively.
1. Large-small scale Interaction

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Application of the two Methods

One-point Analysis, Left and right hand sides.

Fig.20 Left hand side of the methods.

Fig.21 Right hand side of the methods.
Application of the two Methods

One-point Analysis, modulation results.

\[ R = 0.01, \text{ and } R = 0.12 \text{ for the correlation coefficient for the Mathis et al. and present methods, respectively.} \]
Conclusions:

- By using EMD, instead of filtering, amplitude modulation could be analysed.
- The LS and SS signals, obtained by either filtering or EMD, follow the same path, but the correlation coefficient, $R$, which defines the degree of modulation, may vary.
- Both methods capture the correlation for negative fluctuations, with the same time intervals.
- Very similar $R$ values obtained in two-point analysis, which are 0.26 and 0.29 for the filtering and EMD cases, respectively.
- $R = 0.01$ and $R = 0.12$ obtained in the one-point analysis, for filtering and EMD-based applications respectively. While a reduction is expected for the one-point analysis, due to the indirect effect by footprinting, the filtering-based case claims a too low $R$ value ($R = 0.01$) compared to two-point analysis ($R = 0.26$). The EMD based method declares better correlation in one-point analysis with $R = 0.12$ comparing to $R = 0.29$ in two-point analysis.
- The analysis shows that large/small scales obtained by EMD present higher correlation, especially for one-point analysis.

References:

Shyy model approach to create DBD plasma which is given as equation below:

\[ E(y, z) = E_0 - \frac{E_0 - E_b}{b} z^+ - \frac{E_0 - E_b}{b \tan(\theta)} y^+ \]  

(1)

The Eq. 1 is divided to wall-normal and spanwise components.

\[ E_z(y, z) = E(y, z) \cos \theta, \]  

(2)

\[ E_y(y, z) = E(y, z) \sin \theta. \]  

(3)

\( \theta \) defines the height of the plasma.
Eqs. 2 and 3 are applied in spanwise and wall-normal directions, respectively.

Both experimental (upper) and DNS (bottom) results were obtained in a stagnant flow with a single DBD actuator.

**Fig. 25** Plasma-aligned velocity, wall-normal velocity and vorticity, respectively. POIiERS experimental data.

**Fig. 26** Plasma-aligned velocity, wall-normal velocity and vorticity, respectively. DNS.
Multiple DBD Actuators by POITIERS

Sinusoidal Application Case (Stagnat Flow)

**Figure 27** Experimental study.

- **a)** Test case.
- **b)** Wall-normal velocity created by the plasma.
- **c)** Spanwise velocity created by the plasma.
Multiple DBD Actuators by CHALMERS

Multiple actuators, $s$ defines the space between actuators.

![Diagram of Multiple DBD Actuators](image)

**Fig. 28** Electric field, $E(y, z)$, illustration by Shyy model for multiple DBD actuators.

**Fig. 29** Sinusoidal part of the force.
Multiple DBD Actuators by CHALMERS

Sinusoidal Application Case (Stagnat Flow)

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Eqs. (2),(3) are modified by adding a spanwise oscillation:

\[ F_z(y, z) = Dc \ E(y, z) \ \cos \theta \sin(2\pi x^+ / \lambda^x) \],
\[ F_y(y, z) = Dc \ E(y, z) \ \sin \theta \sin(2\pi x^+ / \lambda^x). \]

Fig. 30 DNS study.

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An experimental study by POITIERS

Fig. 31 Experimental applied force configuration and streamwise velocity contours.
1. Large-small scale Interaction

New Approximation

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A DNS study by CHALMERS

Fig.32 DNS, applied force configuration and streamwise velocity contour.
Conclusion:
- We have similar results for the matching test cases with experimental studies.
- Local skin friction reduction is observed.
Thank you for your attention.

References: