Harvesting energy from turbulence in boundary layers by using piezoelectric generators

Yiannis Andreopoulos
Dogus H. Akaydin
Niell Elvin

Mechanical Engineering, CCNY
**Piezoelectric effect**

### Converse Pizoelectric Effect

- **$T$=Stress tensor**
- **$S$=strain tensor**
- **$s$=compliance**
- **$S=sT$**

\[
\{S\} = [s^E]\{T\} + [d^E]\{E\}
\]

### Direct Pizoelectric Effect

- **$D$=Electric displacement**
- **$E$=Electric field strength**
- **$\epsilon$=permittivity**
- **$P$=dipole density**
- **$D=\epsilon E+P$**

\[
\{D\} = [d]\{T\} + [\epsilon^T]\{E\}
\]

\[
[d] = \text{Matrix of piezoelectric coefficients}
\]

\[
d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_i}{\partial E_j}\right)^T
\]
Piezoelectric Beam

\[ F(t) = F_o \sin(\omega t) \]

\[ m \ddot{y}_t + c \dot{y}_t + ky_t - \Theta v = F \]

(Actuator Eqn)

\[ \Theta \ddot{y}_t + C \dot{v} = -\frac{v}{R} = I \]

(Sensor Eqn)

If \( R = \infty \) (open circuit) then

\[ v = \frac{-\Theta}{C} y_t \]

\( \Theta \) “Electromechanical coupling coefficient”
Piezoelectric phenomena

PVDF: Polyvinylidene fluoride
L = 30 mm; w = 16 mm;
t = 0.172 + 0.028 = 0.2 mm

AC-coupled
Charge cancellation

2\textsuperscript{nd} mode leads to charge cancellation
Previous work

Allen & Smits (2001)


Figure 1. Geometry of oscillating membrane behind a flat plate.

Figure 2. System concept for a scalable wind-to-electric conversion system based on the use of piezoelectric materials.
Flows Investigated

Wake of Cylinder at $Re=10,000$: Resonance forcing

Boundary Layer at $Re_0=7,000$: Random forcing
Objective: Explore the use of Piezo beams in boundary layer

Stokes number, $St = \omega L^2/\nu = 18,000$

i.e. $L, \delta_a^2 = \nu/\omega$

$Re = U_0 L/\nu = 21,000$

Strouhal number: $Str = St/Re = \omega L/U_o = U_r/U_o = 2$ to $0.54$

Two flow cases: $L/\delta = 0.3$ & $0.15$

$Re_\theta = 2,500$ to $7,800$

$\delta = 95\text{mm}$ to $130\text{mm}$
4 x 4 Wind Tunnel
Estimated tip displacement

Tip Deflection vs Time

\[ y_t = -\frac{C}{\Theta} v \]
Typical amplitude spectrum

Amplitude vs Frequency

Amplitude [V]

Frequency [Hz]

43 Hz
$210 \times 10^{-3} \text{V}$

317 Hz
$6 \times 10^{-3} \text{V}$
Output power across BL at $Re_\theta = 6800$
Boundary Layer Results

Average Electrical Power vs Wall Clearance and Freestream Velocity

Power [$\mu$W] vs Velocity [m/s] and Wall Clearance [mm]

Plot showing the relationship between power, velocity, and wall clearance.
Piezo foil horizontal in boundary layer
Piezo-foil vertical in boundary layer
Output power across BL at $\text{Re}_{\theta}=6800$: Effect of length

\[ \text{Power (\mu W)} \]

![Graph showing the effect of length on output power across BL at Re$_\theta=6800$. Graph includes data points for different values of y/\delta and L/\delta, with lines indicating the effect of varying L/\delta and Power with L=30mm and Power x 40 with L=15mm.}
Power across BL with piezo beam length $L=15\text{mm}$

$f_n$ is 4 times higher here
Forces on piezo foil in a time dependent flow

\[
\int n_x p - n_1 \tau_{ix} dS = F_x = \int \{ n_x p - n_1 \tau_{ix} + \rho n_i U_i (U_x - V_n) \} dS + \rho \frac{\partial}{\partial t} \int \int U_x dV
\]

\[
\int n_y p - n_1 \tau_{iy} dS = F_y = \int \{ n_y p - n_1 \tau_{iy} + \rho n_i U_i (U_y) \} dS + \rho \frac{\partial}{\partial t} \int \int U_y dV + \int \int \rho g dV
\]

\[
F_x = 1/2 C_D \rho U(t) U(t) + C_{xm} A T \rho dU(t) / dt
\]

\[
F_y = 1/2 C_L \rho U(t) U(t) + C_{ym} A T \rho dU(t) / dt
\]

**Inertia effects**

Work by Drag matters when foil moves forward.

If it remains stationary, it does not.

Parasitic & interference drag

Piezo foils may act like LEBUs and reduce interference drag

**APS-DFD09**
Conclusions

1. Explore the performance of piezoelectric beams in TBL
2. There is a three way interaction between fluid solid and electric fields
3. Horizontally placed beams provide higher output than vertically placed
4. Random forcing away from resonance reduces output power
5. Drag penalty will be investigated experimentally. Interference drag maybe reduced due to “LEBU devices” effects