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Total bottom shear stress for oscillatory flow over wave-generated sand ripples

Yuan Jing, Ph.D., Assistant Prof.

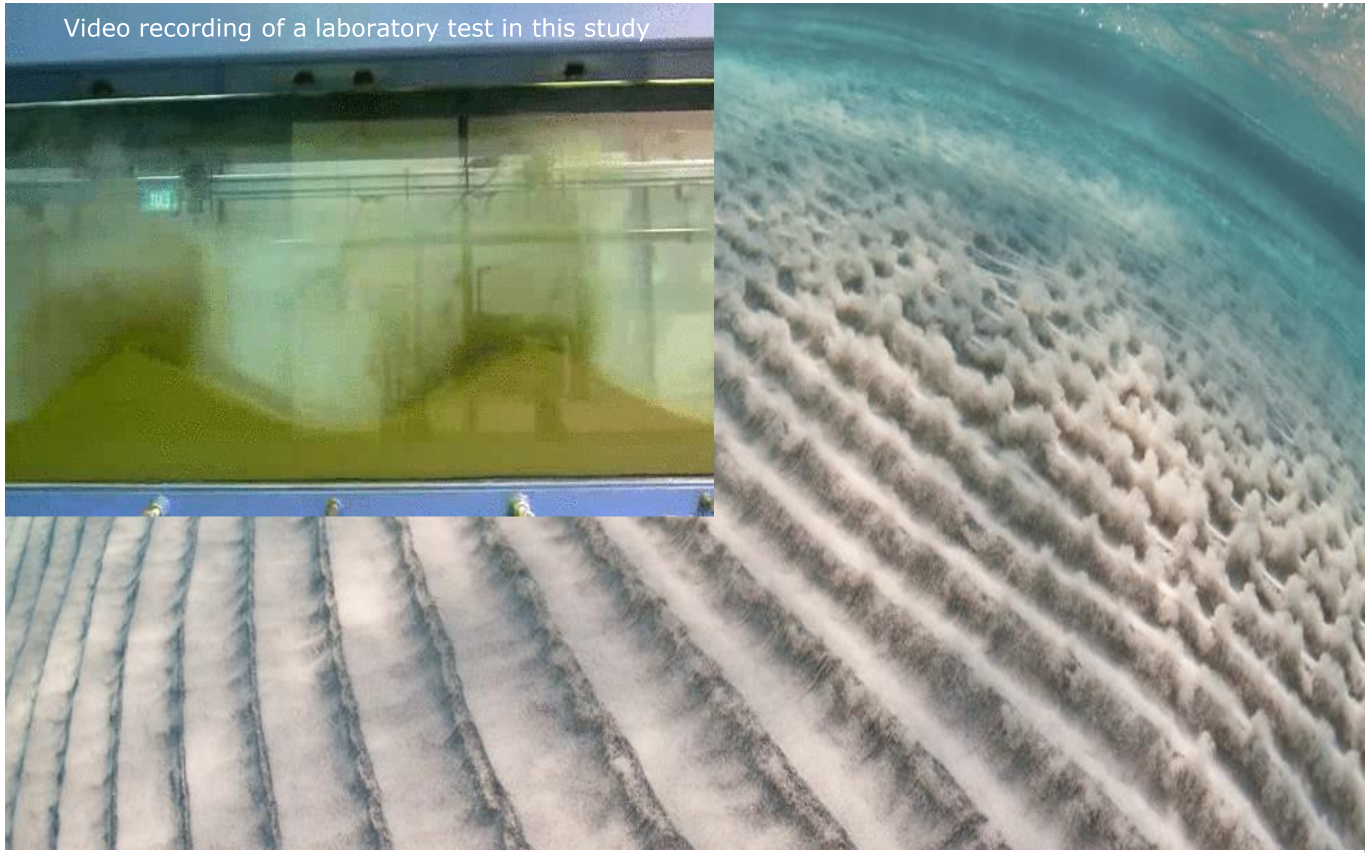
National University of Singapore, Dept. of Civil and Environ. Eng.

Wang Dongxu, Ph.D. student

National University of Singapore, Dept. of Civil and Environ. Eng.




Motivation: wave-generated sand ripples



http://www.naturephotoblog.com/2012/02/28/10356/alex-mustard

Coastal waves generate (vortex) ripples on a sandy seabed.

Coherent vortex motion is the dominant feature of local boundary layer flow

Ripples → enhanced flow resistance (bottom shear stress)

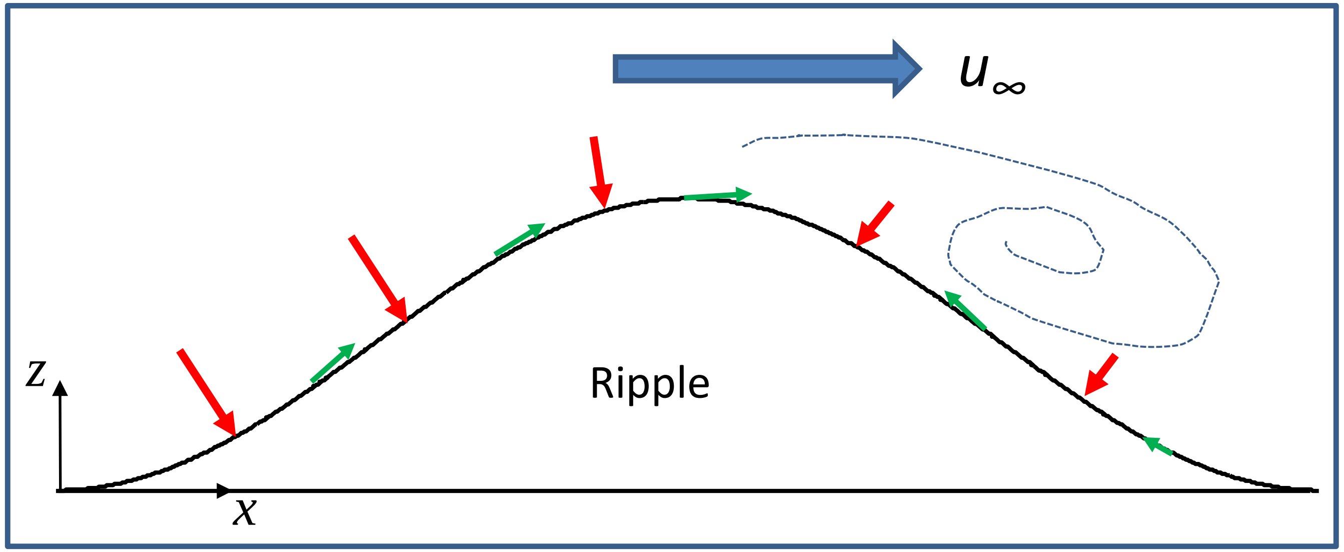
Form drag for oscillatory flows over vortex ripples

$$F_R = \int_0^\lambda \frac{p_\eta}{\rho}\frac{\partial \eta}{\partial x}dx + \int_0^\lambda \frac{\tau_\eta}{\rho}dx$$

Form drag Skin friction

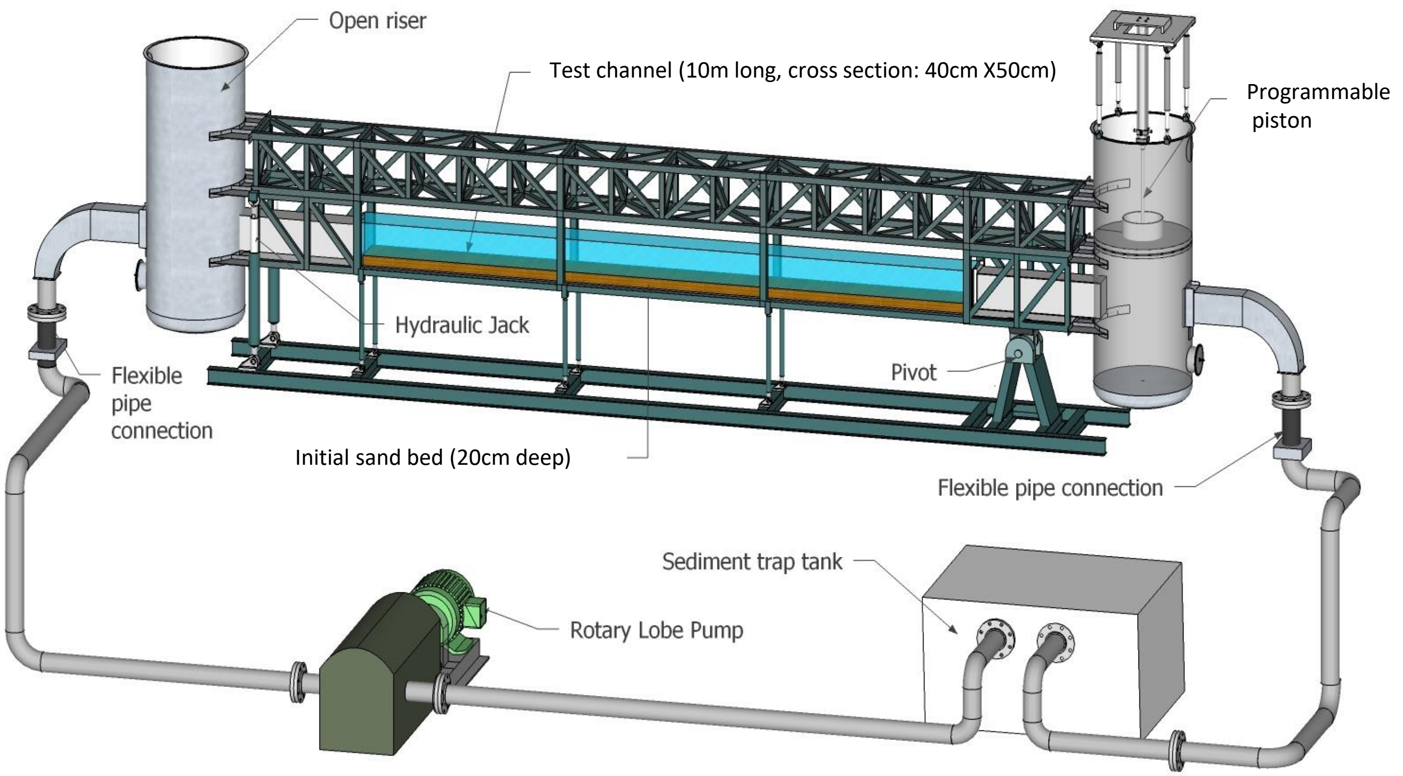
$$p_\eta = p - p_\infty ,$$

$$-\frac{1}{\rho}\frac{\partial p_\infty}{\partial x} = \frac{\partial u_\infty}{\partial t}$$



- Form drag is usually much larger than skin friction
- Important for understanding wave energy dissipation E_d, wave-current interaction, etc.
- Can be indirectly measured from E_d.
- Very little direct and full-scale measurements

Research facility: oscillatory water tunnel



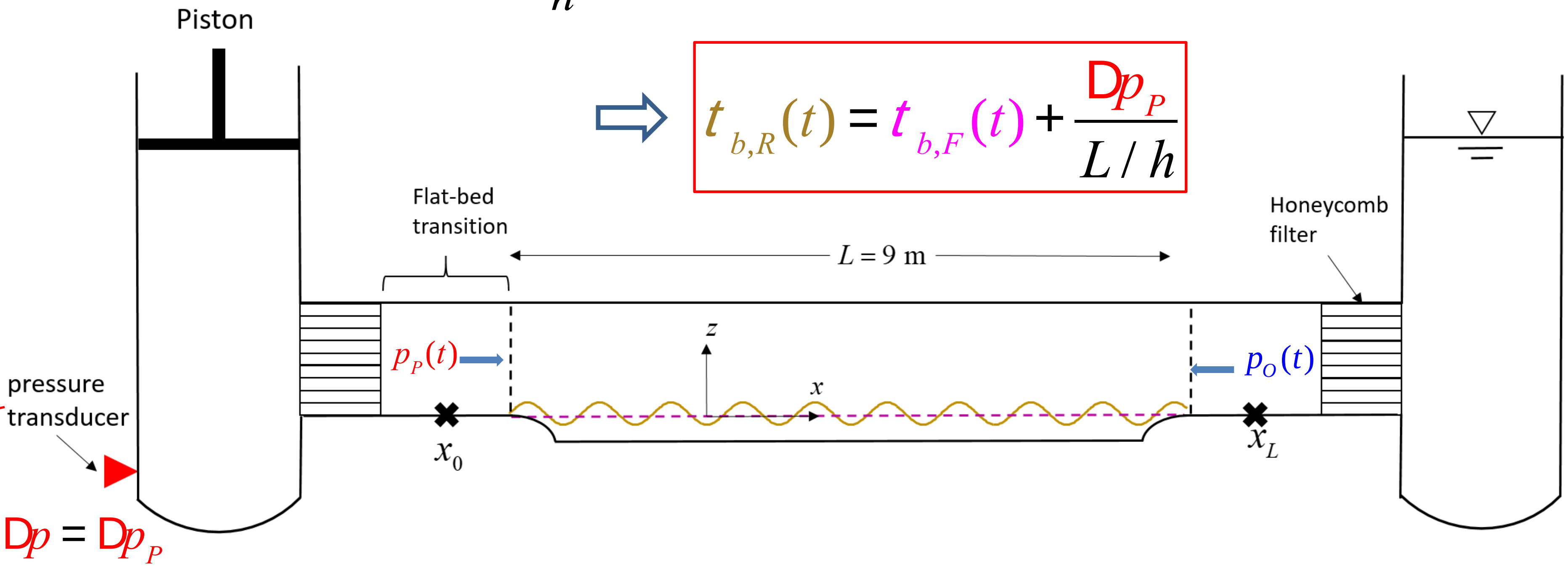
- 10 m-long test section with a 40cm-by-50 cm cross section
- Oscillatory flow with Ab<2m and T>3s
- 20cm-deep movable bed (9 m long)
- Precise flow generation
- A laser-based bottom profiler for measuring ripple shape
- A PIV system for 2D flow measurements

A pressure-based measurement technique

- p_P-p_o drives the oscillatory flow.
- p_P increases as bottom shear stress increases.
- p_o only depends on flow condition.
- For a pair of tests (flat bed vs. rippled bed) the difference in p_P is proportional to change in total bottom shear stress
- Same pressure difference inside the piston-end riser

$$\frac{L}{h}\left[\tau_{b,R}(t) - \tau_{b,F}(t)\right] = \left[p_P(t)\right]_R - \left[p_P(t)\right]_F = \Delta p_P$$

$$\Rightarrow \boxed{\tau_{b,R}(t) = \tau_{b,F}(t) + \frac{\Delta p_P}{L/h}}$$



Test conditions

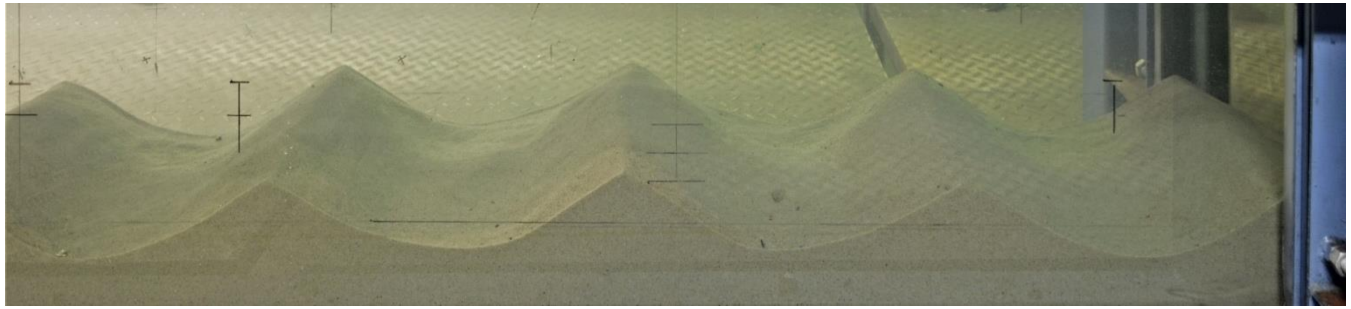
$$u_\infty(t) = U_\infty \cos\left(\frac{2\pi}{T} t\right)$$

$$\mathrm{Re}_w = \frac{A_b U_\infty}{\nu}$$

Test ID	A_b [m]	T [s]	ψ_{wmd}	U_∞ [m/s]	H_R [mm]	λ [mm]	No. of ripples	duration [h]	Re_w
Ta030	0.30	6.25	0.064	0.302	77	396	21	4.0	$9.1 \cdot 10^4$
Ta040	0.40	6.25	0.105	0.402	92	456	18	3.2	$1.6 \cdot 10^5$
Ta050	0.50	6.25	0.153	0.503	96	479	17	1.4	$2.5 \cdot 10^5$
Ta060	0.60	6.25	0.21	0.603	109	581	14	1.0	$3.6 \cdot 10^5$
Ta080	0.80	6.25	0.344	0.804	127	689	12	0.5	$6.4 \cdot 10^5$
Ta100	1.00	6.25	0.506	1.005	119	803	11	0.3	$1.0 \cdot 10^6$
Tc045	0.60	8.33	0.118	0.452	124	607	13	1.1	$2.7 \cdot 10^5$
Tc060	0.80	8.33	0.194	0.603	142	742	12	0.8	$4.8 \cdot 10^5$
Tc075	1.00	8.33	0.285	0.754	178	998	9	0.3	$7.5 \cdot 10^5$
Td044	0.70	10	0.107	0.44	186	829	10	3.3	$3.1 \cdot 10^5$
Td057	0.90	10	0.165	0.565	207	1242	7	1.5	$5.1 \cdot 10^5$

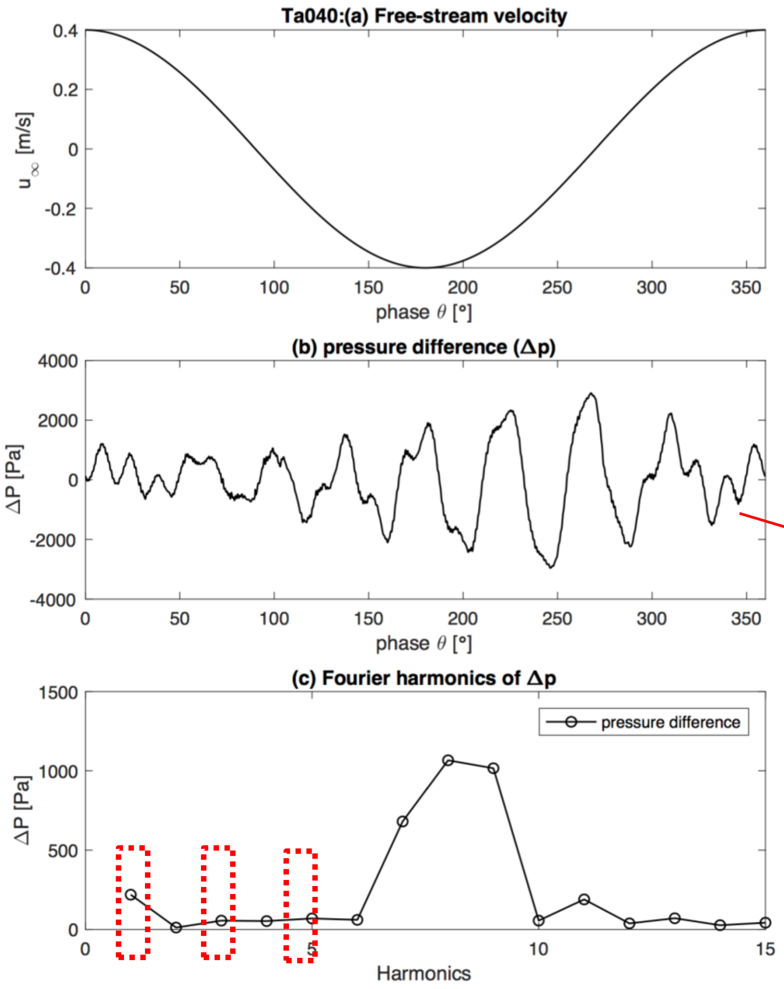
Highlights:

- Coarse sand (d_{50}=0.51mm)
- All 2D equilibrium ripples
- 11 tests with
  - $Re_w = 9.1 \cdot 10^4 - 7.5 \cdot 10^5$.
  - T=6.25-10 s
  - A_b=0.3-1.0 m, U_∞=0.3-1.0 m/s
  - Ripple height H_R: 77-207 mm
  - Ripple length λ: 396-1242 mm



Data correction

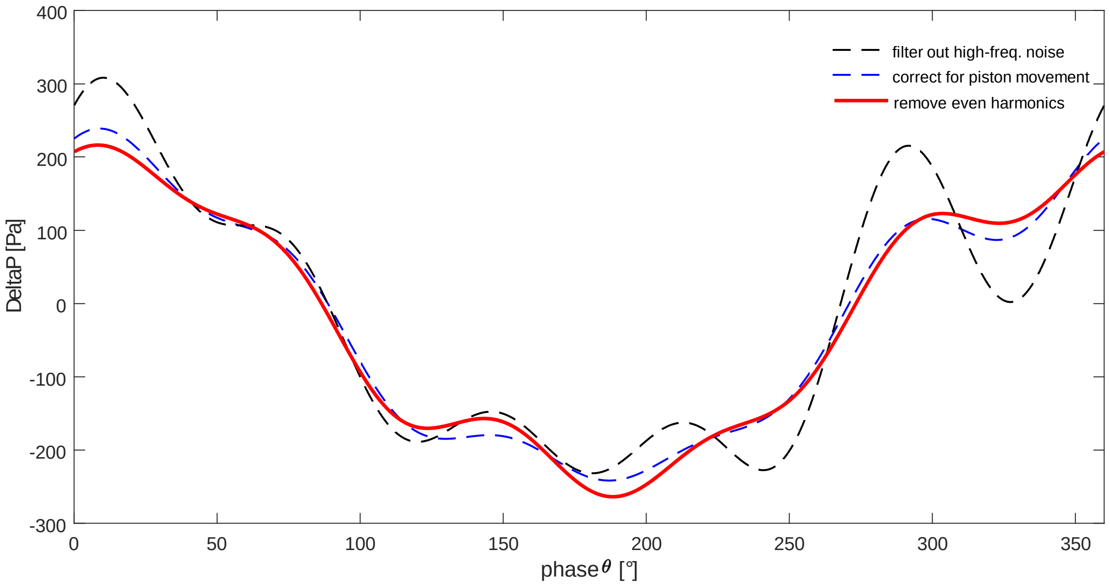
Example: Ta040 (U_{bm}=0.4m/s, T=6.25s, H_R=96mm, λ=479mm)



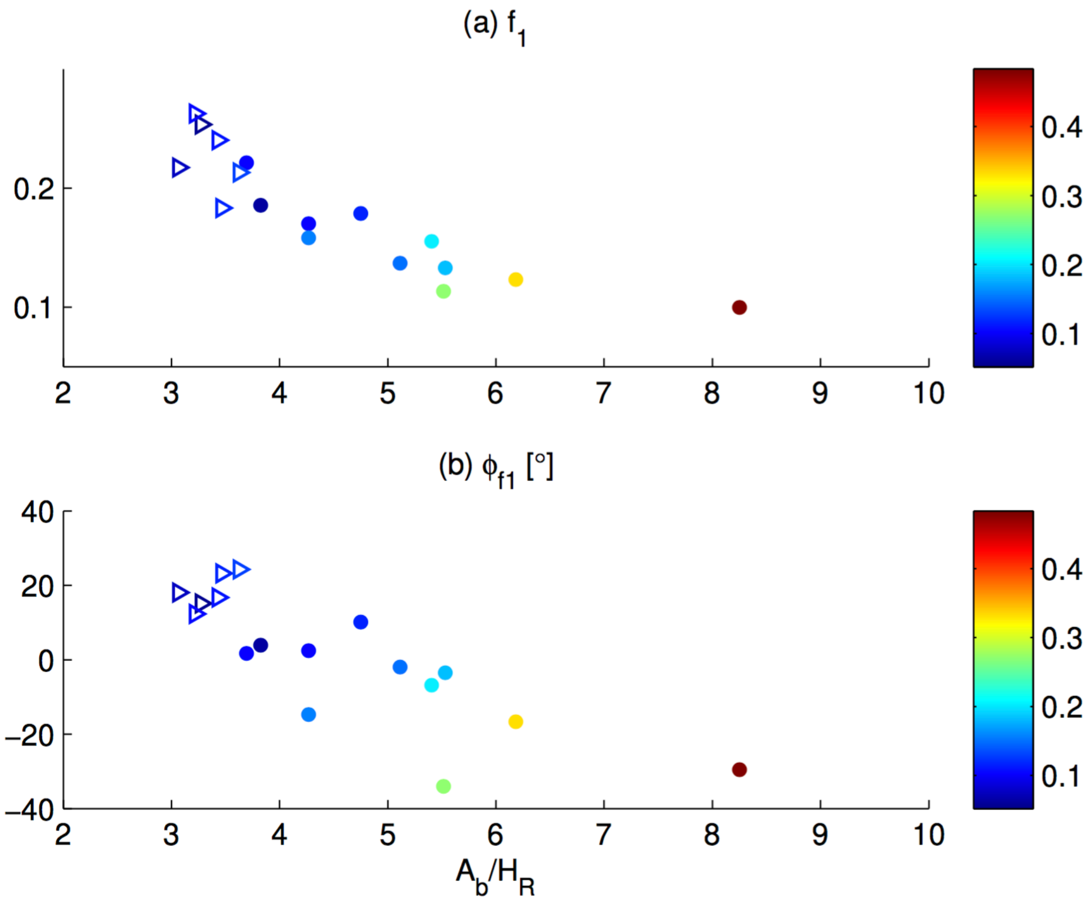
Correction:

- Remove high-freq. harmonics (>5th harmonic)
- Correct for imperfect piston movement
- Remove even harmonics

Only keep 1st , 3rd and 5th harmonics



First-harmonic total bottom shear stress

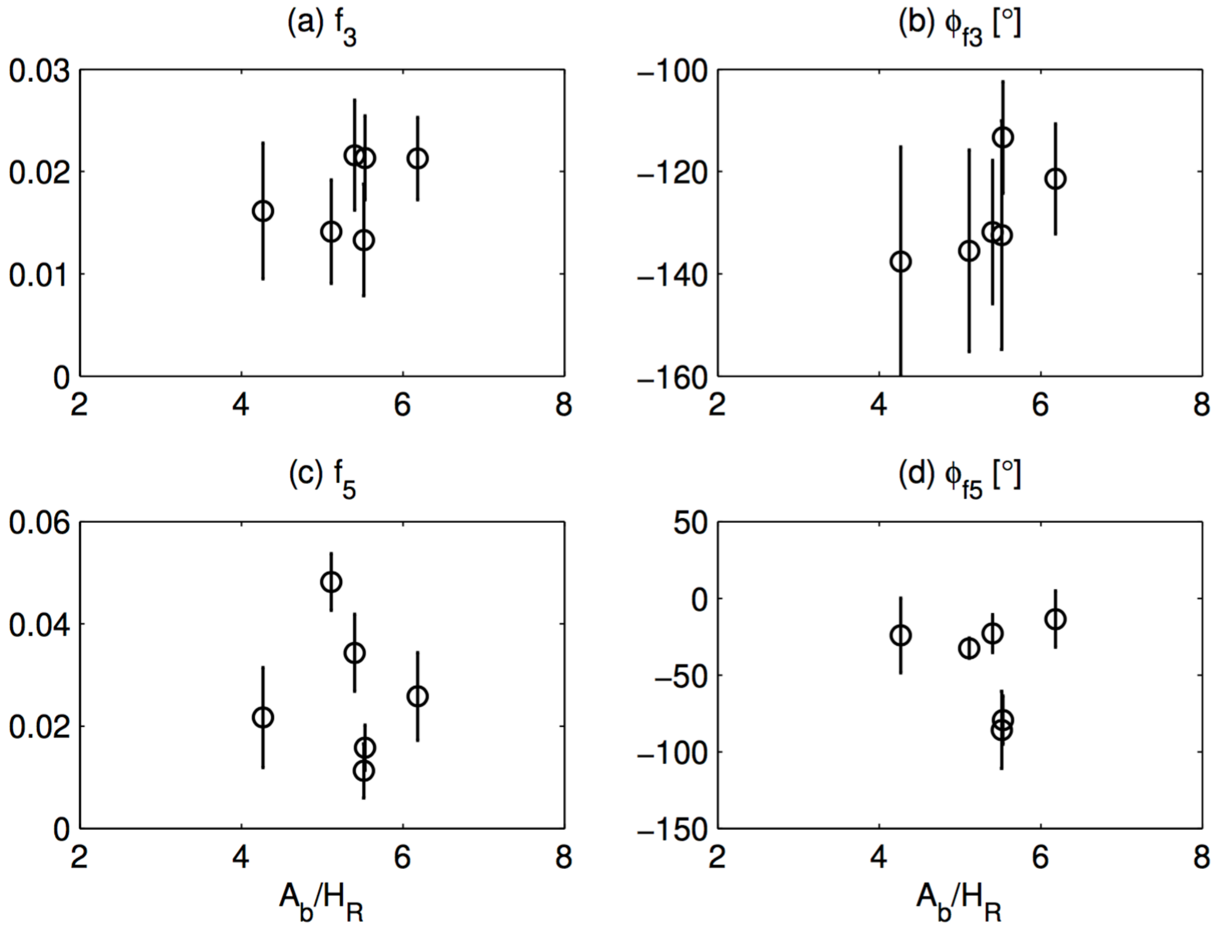


A_b/H_R: inverse of relative ripple height (→ ∞ for flat bed)

$$f_t = \frac{2\tau_b}{\rho U_\infty^2} = \mathrm{Re}\left(\sum_{n=1,3,5} f^{(n)} e^{in\omega t}\right) = \sum_{n=1,3,5} f_n \cos(n\omega t + \phi_{fn})$$

- 1st harmonic is the dominant one
- Amplitude decreases with roughness or shields parameter: wash-off by strong flows
- In phase with free-stream velocity

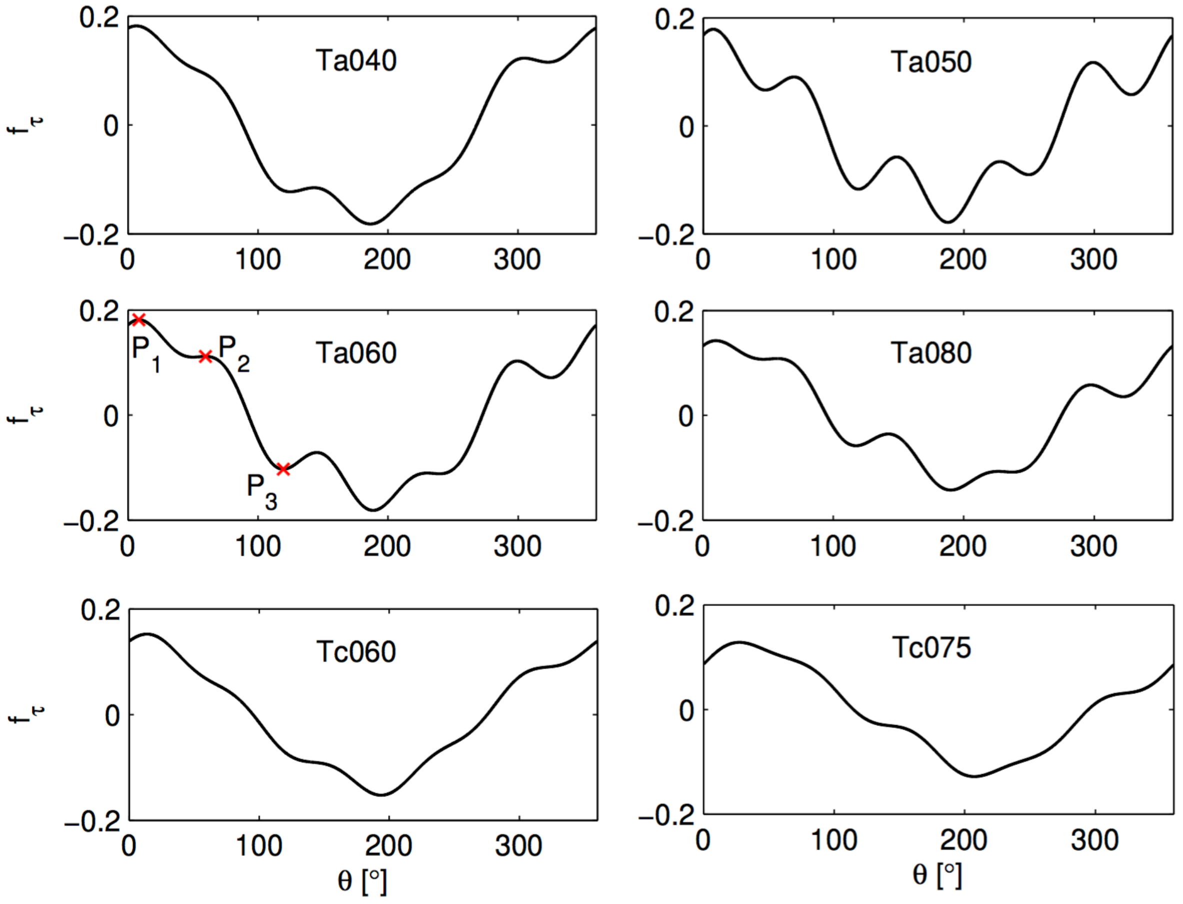
Higher-order harmonics



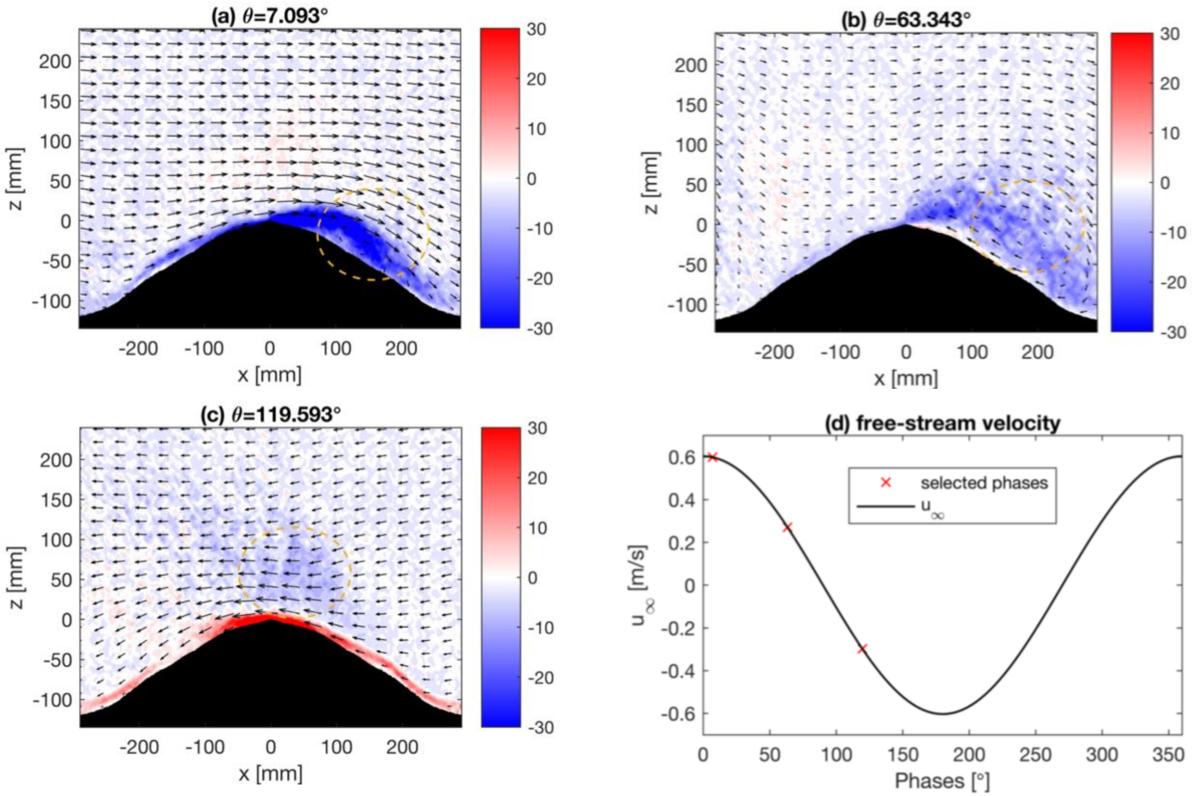
$$f_t = \frac{2\tau_b}{\rho U_\infty^2} = \mathrm{Re}\left(\sum_{n=1,3,5} f^{(n)} e^{in\omega t}\right) = \sum_{n=1,3,5} f_n \cos(n\omega t + \phi_{fn})$$

- 3rd and 5th harmonics suffer from large experimental error (6 of 11 tests are acceptable)
- Magnitude is of O(0.01), 5th harmonic is even larger than the 3rd harmonic
- No clear trend of variation

Intra-period variation of total bottom shear stress

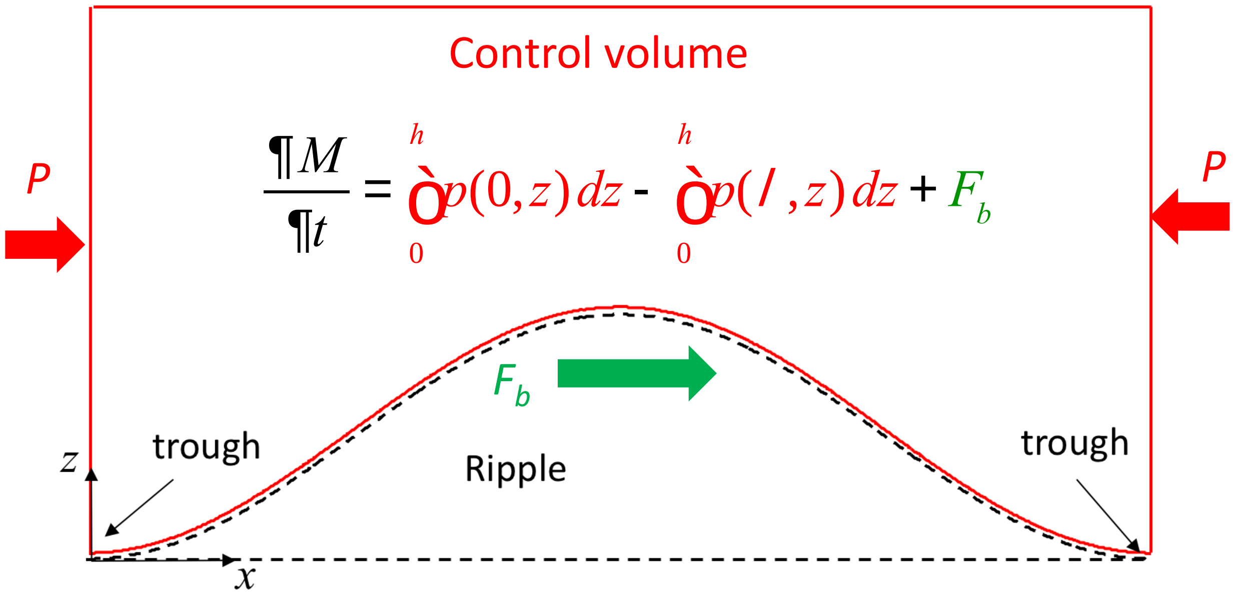


Example: Ta060 (U_{bm}=0.60m/s, T=6.25s, H_R=109mm, λ=508mm)



Hypothesis: multiple peaks are associated with coherent vortex motion.

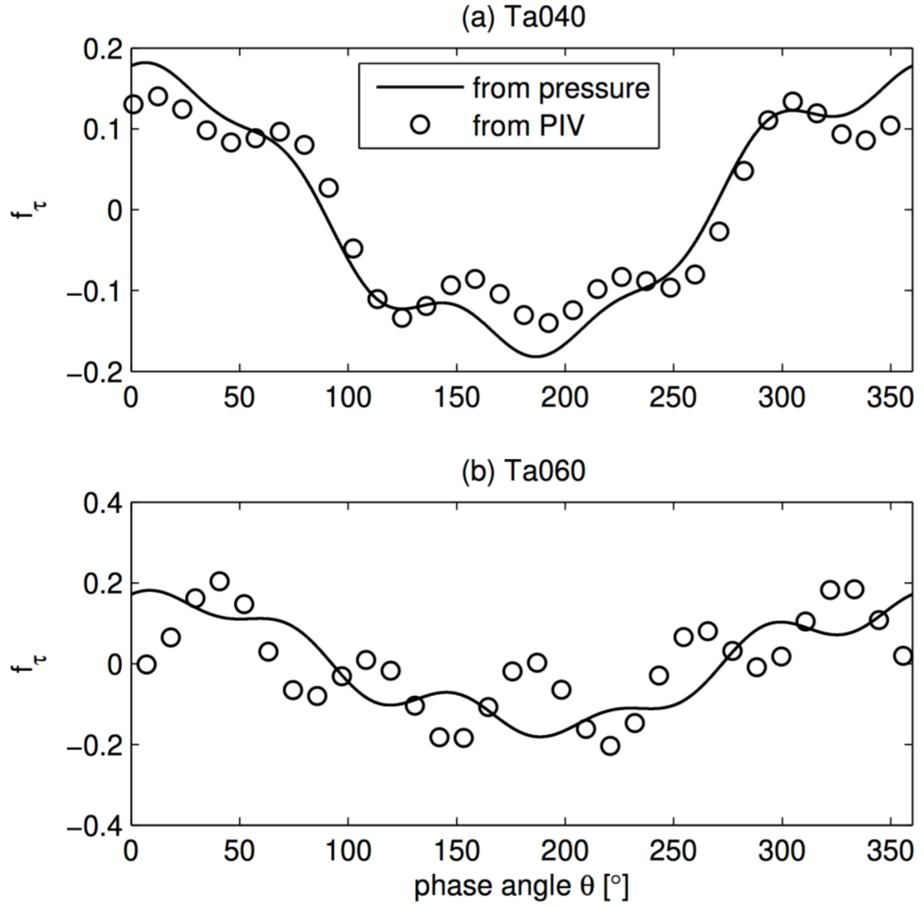
Comparisons with PIV-based measurements



$$\frac{\partial M}{\partial t} = \int_0^h p(0,z)\,dz - \int_0^h p(\lambda,z)\,dz + F_b$$

Some algebra→ total bottom shear stress can be estimated with the velocity profile at trough

$$\tau_b = \frac{\partial}{\partial t}\left[\int_0^h \left(u - u_\infty\right) dz\right] - \frac{\partial u_\infty}{\partial t}\frac{V_{ripple}}{\lambda}$$



Reasonable agreement for major feature (1st harmonic), but poor agreement higher-order harmonics.

Conclusion

- A pressure-based technique is developed for measuring total bottom shear stress over wave-generated vortex ripples.

- Total bottom shear stress is dominated by its first-harmonic Fourier component, which is almost in-phase with the free-stream velocity.

- PIV measurements suggest that coherent vortex motion controls the intra-period variation of total bottom shear stress.

- Good agreement between pressure- and PIV-based measurements for the first harmonic.