Hydrodynamic load exerted on

a moving bundle of hollow fibers using constraint dissipative hydrodynamics: Hydro-Rattle simulation

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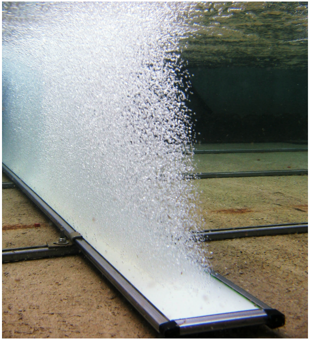
Outline

Submerged Membrane Bioreactor: Some Cases

Hon. WWWTP, future MBR for greenhouse gas emissions (↓)

EnoQua Membrane Bioreactor

How to Reduce HF Fouling: Blowing → SHAKING



AERO******

Kolon, LENA

- "Low Energy No Aeration" (LENA)
  1. a new *counter-intuitive* membrane technology:
  2. energy saving: $\approx 25\%$
  3. shaking consumes less energy than blowing.
  4. video 1 & video 2

Does Dynamics of Hollow Fiber Follow Wave Equation? NO!

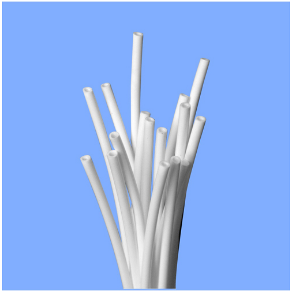
(a) LENA

(b) Vibrating guitar strings

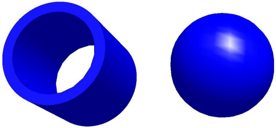
In (b), string image[1]

[1] https://www.sciencesource.com/archive/Vibrations-in-Guitar-Strings-SS2781967.html

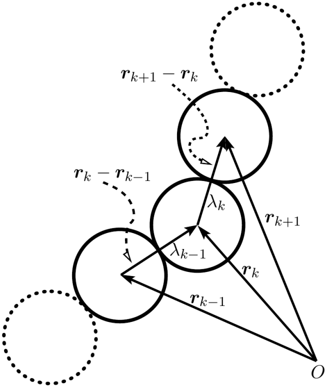
Hollow Fiber Segment vs. Equivalent Sphere



(a) fiber bundle

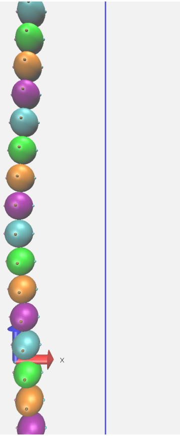


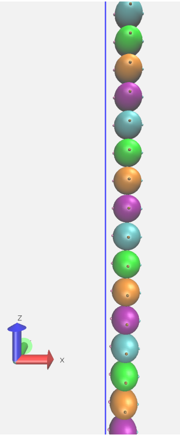
(b) fiber seg. & equiv. sphere



(c) fiber as linked sphers

Hollow Fiber Segment vs. Equivalent Sphere (cont'd)





- Sphere colors are just for visualization
- Black dots (6 per sphere) is to see sphere rotation.

Theoretical approaches

Holonomic constraints: center-to-center distance

$$\sigma_k = (\boldsymbol{r}_k - \boldsymbol{r}_{k+1})^2 - d_{k,k+1}^2 = 0 \tag{1}$$

Non-Holonomic constraints: position-velocity orthogonality

$$(\boldsymbol{r}_k - \boldsymbol{r}_{k+1}) \cdot (\boldsymbol{v}_k - \boldsymbol{v}_{k+1}) = 0 \tag{2}$$

Total Force = External + Internal

1. External:
    1. gravitational force (vector-wise)
    2. hydrodynamic force/torque (tensor-wise)
2. Internal
    1. holonomic
    2. non-holonomic constraint forces

Constraint Forces

Holonomic Constraint Force on sphere k

$$m_k \boldsymbol{a}_k^c = \lambda_{k-1} \left(\boldsymbol{r}_{k-1} - \boldsymbol{r}_k \right) - \lambda_k \left(\boldsymbol{r}_k - \boldsymbol{r}_{k+1} \right) \tag{3}$$

where λ is the Lagrange multiplier, to be instantaneously updated as responding to non-internal forces.

Non-holonomic Constraint Force on sphere k

$$m_k \boldsymbol{a}_k^n = \kappa_{k-1} \left(\boldsymbol{r}_{k-1} - \boldsymbol{r}_k \right) - \kappa_k \left(\boldsymbol{r}_k - \boldsymbol{r}_{k+1} \right) \tag{4}$$

has the same mathematical form, but $\kappa \neq \lambda$.

Constraint Dynamics Simulation

- How to efficiently calculate/update λ and κ for evol.

External Forces

Gravitational + Buoyant Forces

$$\boldsymbol{F}_j^G = \Delta m_j \boldsymbol{g} \tag{5}$$

where $\Delta m_j = m_j - m_f$, and \$m_{f}is the mass of fluid.

Hydrodynamic Forces/Torques ← Stokesian Dynamics

$$\begin{bmatrix} \boldsymbol{U}^\infty - \boldsymbol{v}_j \\ \Omega^\infty - \boldsymbol{\omega}_j \\ \boldsymbol{E}^\infty \end{bmatrix} = \sum_{k=1}^{N_p} \begin{bmatrix} \boldsymbol{a}_{jk} & \tilde{\boldsymbol{b}}_{jk} & \tilde{\boldsymbol{b}}_{jk} \\ \boldsymbol{b}_{jk} & \boldsymbol{c}_{jk} & \tilde{\boldsymbol{h}}_{jk} \\ \boldsymbol{g}_{jk} & \boldsymbol{h}_{jk} & \boldsymbol{m}_{jk} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{F}_k^H \\ \boldsymbol{T}_k^H \\ \boldsymbol{S}_k^H \end{bmatrix} \tag{6}$$

where $\left[\boldsymbol{F}_k^H, \boldsymbol{T}_k^H, \boldsymbol{S}_k^H\right]^{\text{tr}}$ is hydrodynamic force, torque, stresslet vectors, in an ambient flow field:

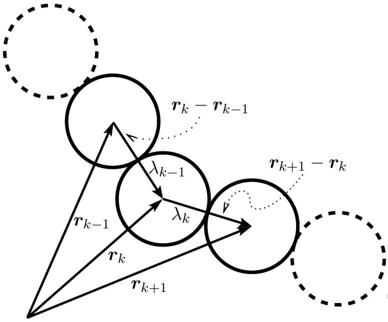
$$\boldsymbol{v}^D\left(\boldsymbol{r}_j\right) = \boldsymbol{U}^\infty + \boldsymbol{\Omega}^\infty \times \boldsymbol{x} + \boldsymbol{E}^\infty : \boldsymbol{x} \quad \text{for} \quad \boldsymbol{x} \in S_j \tag{7}$$

Grand Governing Equation for N_p Connected Spheres

… requiring to solve a linear system of $11N_p \times 11N_p$ matrix.

$$\begin{bmatrix} m_k & 0 \\ 0 & I_k \end{bmatrix} \begin{bmatrix} \boldsymbol{a}_k \\ \boldsymbol{\alpha}_k \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}_k^H \\ \boldsymbol{T}_k^H \end{bmatrix} + \begin{bmatrix} \boldsymbol{F}_k^E \\ 0 \end{bmatrix} + \begin{bmatrix} \boldsymbol{F}_k^C \\ 0 \end{bmatrix} \qquad (8)$$

- If $N_p = 1,000$, the no. of element = 121,000,000
- Memory = element no. times 8 byte → ≈1.0 GB.



Simulation parameters: rack and fibers

	Variables	Value	Value
Rack	Fiber length [mm], L_f	1000	2000
	Number of spheres, N_p	500	1000
	Stack height [mm], $H = L_f/(1 + R_{st})$	998	1996
	Oscillation Amplitude [mm], A	6.0	12.0
	Oscillation frequency [Hz], ω	0.46	0.46

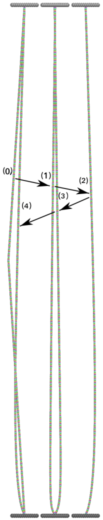
Table: Simulation parameters of the rack and fibers, where the oscillation amplitude is calculated as $A = 0.06\,L_f$ and the stack ratio of $R_{\mathrm{st}} = 0.2\,\%$ is used. Based on the common frequency, the period of the rack oscillation is calculated as $\tau = 2.1739$ s.

Simulation parameters: rack and fibers

	Variables	PVDF	PET
Fiber	Solid density, ρ_s	1.780	1.380
	Outer diameter [mm], $d_o = 2a_f$	2.000	2.000
	Inner diameter [mm], $d_i = 2a'_f$	1.600	0.700
	Thickness [mm], $a_f - a\prime_f$	0.200	0.650
	Porosity [-], ϵ	0.650	0.650
	Water-filled fiber material density, $\bar{\rho}_f$	1.273	1.133
	Mass of cylindrical segment [mg], m_s	6.901	7.017
Sphere	Volume [mm^3]	4.189	4.189
	Specific gravity [–], s_g	1.647	1.675

Table: Simulation parameters of the rack and fibers and equivalent spheres, made of polyvinylidene fluoride (PVDF) and polyethylene terephthalate (PET).

Snapshots during 6 quarter periods



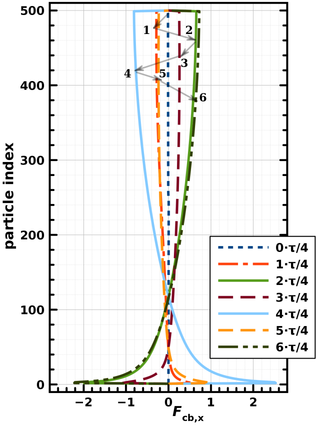
Periodic motion

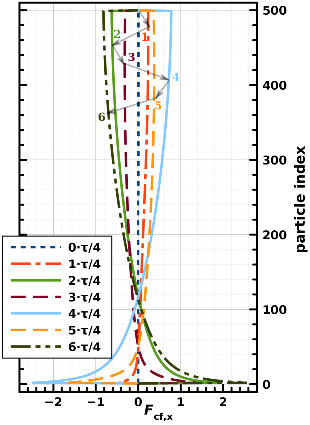
- 0: initial rightmost position
- 1: $t = \tau_{1/4}$ after a **quarter period**
- 2: $t = 2\tau_{1/4}$ after two quarter period
- 3: $t = 3\tau_{1/4}$ after a half period
- 4: $t = 4\tau_{1/4}$ after a full period
- 5: $t = 5\tau_{1/4}$ after 1.25 period
- 6: $t = 6\tau_{1/4}$ after 1.50 period

where $\tau_{1/4} = \tau/4$ is a quarter period.

[Short Chain] Constraint Forces in $x-$ Direction

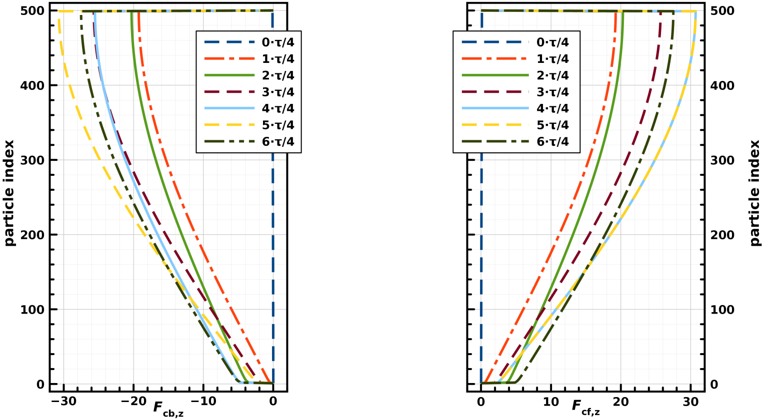
- Backward & forward constraint forces: anti-symmetric.
- Near $z = l_f/4$, i.e., 25% height, almost $F_x^c \to 0$ [nN].





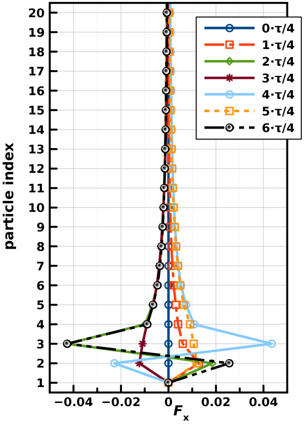
[Short Chain] Constraint Forces in $z-$ Direction

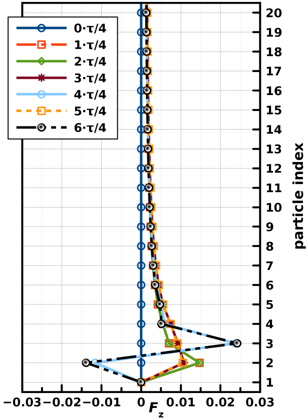
- F_z^c is about 10 times stronger than F_x^c [nN].
- Anti-symmetry appears, but not perfect.



[Short Chain] Total Force in $x-$ and $z-$ Direction

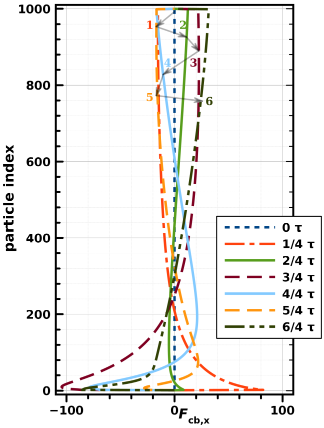
- The net total forces [μN] exerted mostly near the bottom.
- Bottom and top segments can be mechanically reinforced.

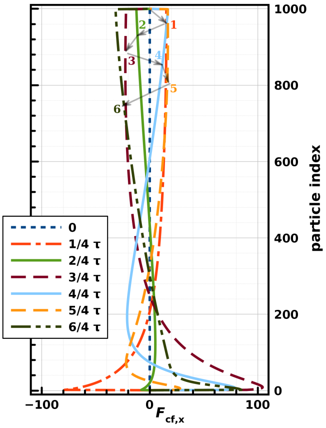




[Long Chain] Constraint Forces in $x-$ Direction

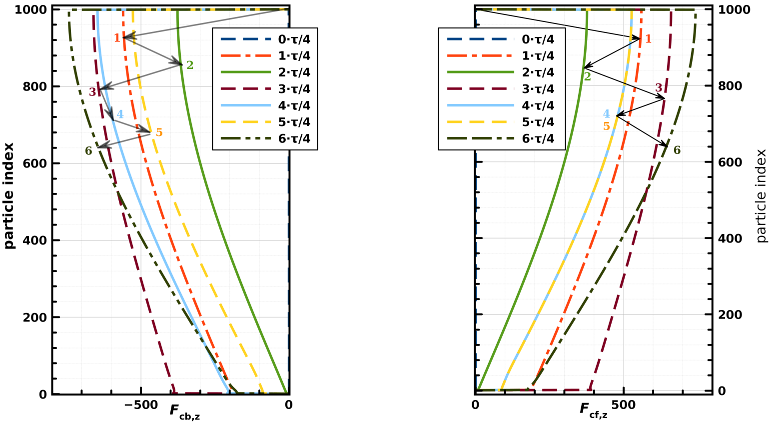
- The zero-force [nN] zone becomes vague.





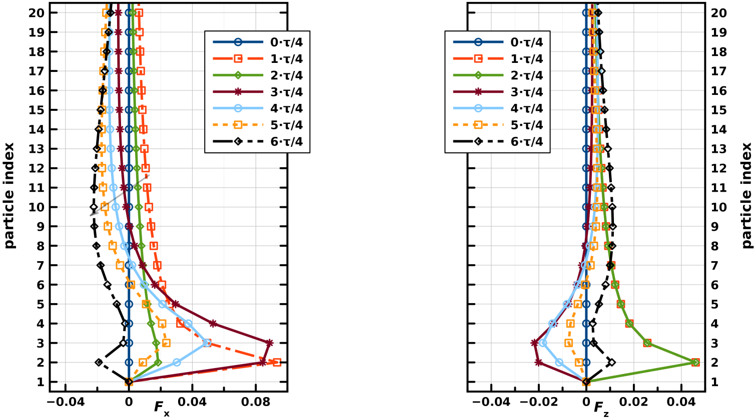
[Long Chain] Constraint Forces in $z-$ Direction

- The periodicity and anti-symmetry become less apparent.
- Constraint force unit [nN]



[Long Chain] Total Force in $x-$ and $z-$ Direction

- Unexpected similarity instead of periodicity in F_{tot} [μN]



Summary

1. A single hollow fiber is modeled as a sphere-connected chain using the equivalent sphere.
2. A short chain reciprocation is within intuitive expectation.
3. A long chain's geometrical configuration is less predictable. Because
    1. the return of the full fiber (i.e., the middle zone) is always after the returning of the rack.
    2. hollow fiber motion is energy-dissipative and entropy-increasing.
    3. periodicity is not fully conserved, generating random/chaotic displacements
    4. perhaps good for fouling reduction, but against the fiber durability.

Acknowledgment

Kolon Industry, Inc.

KOLON INDUSTRIES

KOrea + Ny**LON** = KOLON (from 1957)

Korea Res. Inst. of Ships and Ocean Engineering (KRISO)

For steady support and long-term collaborators …

KRISO

KOREA RESEARCH INSTITUTE OF
SHIPS & OCEAN ENGINEERING

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Questions and Comments?