Optimal Vortex Formation as a Unifying Principle in Biological Propulsion

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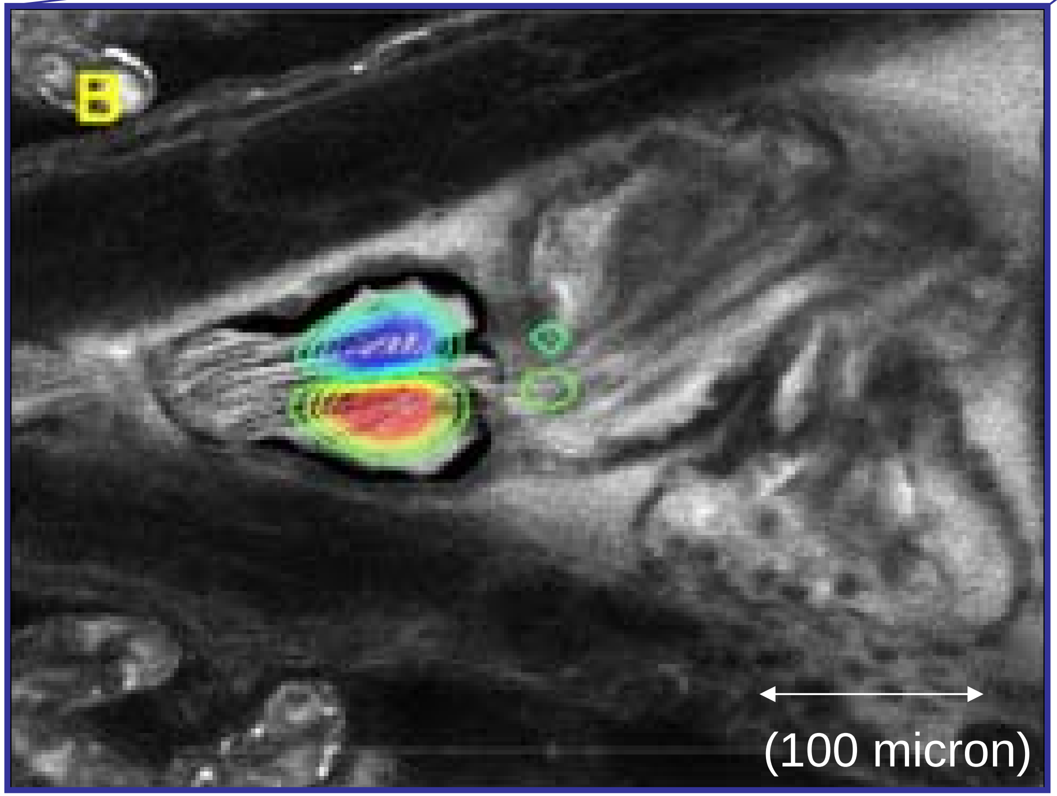
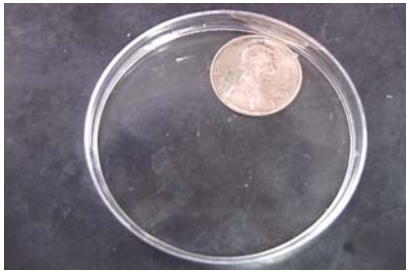
Vortex Rings

A Secondary Eruption of Mt. St. Helens, June 1980 [Photo by Robert P. VanNatta]

Zebrafish (*Danio rerio*) Embryo



1.5 mm long



Koster, Forouhar and Gharib (2002)

Previous Work on Vortex Rings

- Early work: Helmholtz (1858), Kelvin (1869)
- Existence: Hill (1894), Fraenkel (1972), Norbury (1973), and others
- Formation: Saffman (1975, 1978), Pullin (1979), Didden (1979), Glezer (1987)
- Evolution and Turbulent rings: Maxworthy (1972, 1974, 1977), Glezer (1987), and others

Fully-Pulsed Jets:

- Bremhorst *et al.* (e.g., 1979, 1990, and 2000)
- Weihs (1977)

Classical View

Vortex ring "…formation is a problem of **vortex sheet dynamics**, the steady state is a problem of **existence**, their duration is a problem of **stability**, and if there are several we have a problem of vortex **interactions**."

-- P.G. Saffman (1981), emphasis added

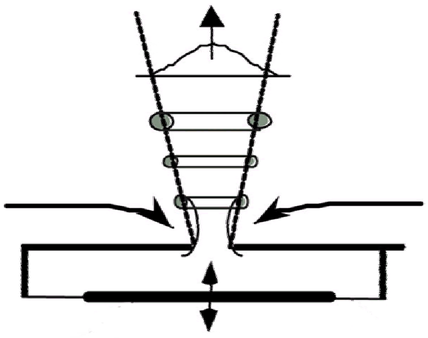
“New” Motivations

Understanding complicated biological flows:

- Aquatic Propulsion
- Cardiac Flows

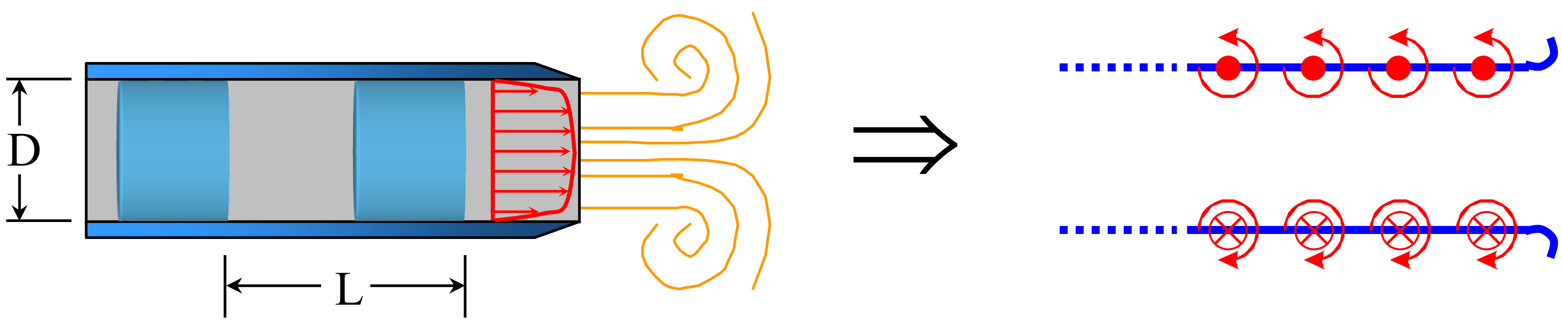
Practical Applications:

- Hydropropulsion /Aeropropulsion
- Micro jet thrusters
- Multi-scale Stirring and Mixing



Canonical Vortex Ring Generator

Vortex rings can be easily generated using a piston-cylinder mechanism to produce a starting jet.



Parameters:

a) Time history of piston velocity

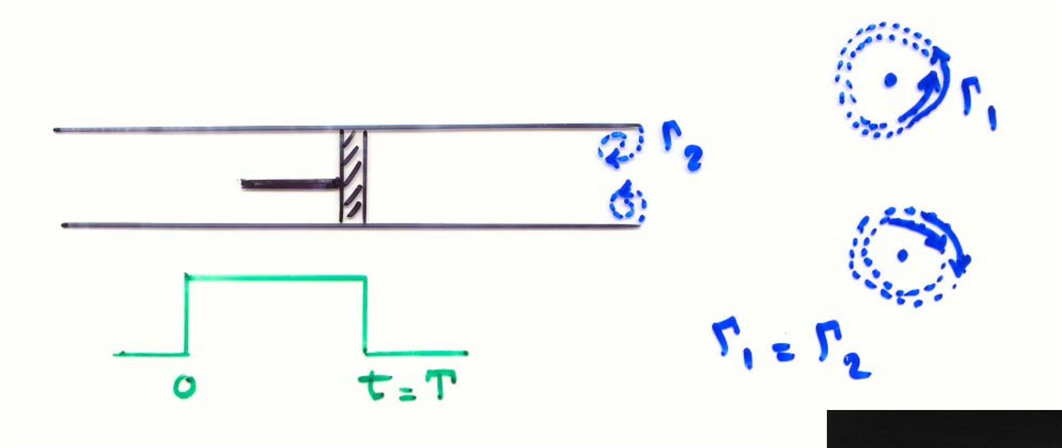
b) L/D

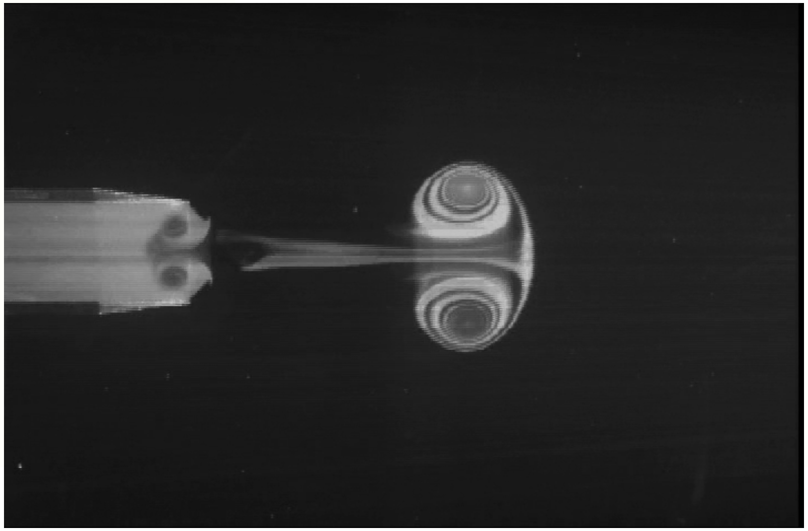
c) Reynolds Number

d) Orifice/nozzle Geometry

Can be viewed as the roll up of a half-"infinite" cylindrical vortex sheet.

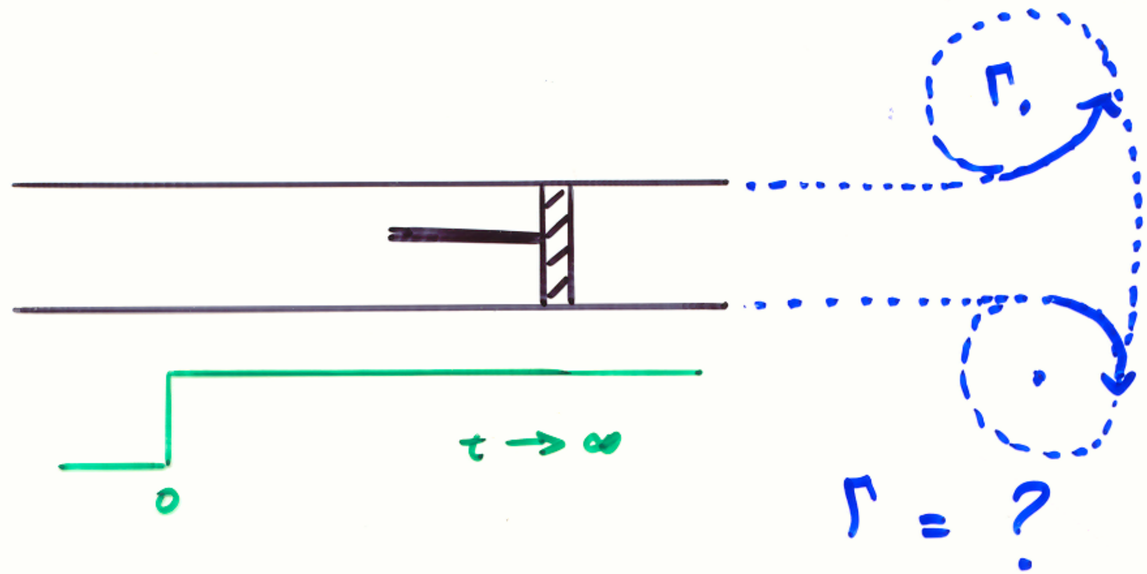
Vortex Ring Formation





P.S. Krueger, J.O. Dabiri and M. Gharib (2003)

Vortex Ring Formation



Vortex Ring Experiments

Glezer *(1981)*	L/D<1
Didden *(1979)*	L/D<2
Kwon and Bernal *(1989)*	L/D<4
Auerbach *(1980)*	L/D<1
Schatzle *(1987)*	L/D<1
Weigand and Gharib *(1994)*	L/D<1
Maxworthy *(1977)*	L/D<3
Sallet *(1974)*	L/D<1

Can we generate arbitrarily large vortex rings?

$$\longleftarrow \; L/D = \left[\int_0^{t} U(\tau)\,d\tau\right] \Big/ D = 2$$

M. Gharib, E. Rambod & K. Shariff, *Journal of Fluid Mechanics* (1998)

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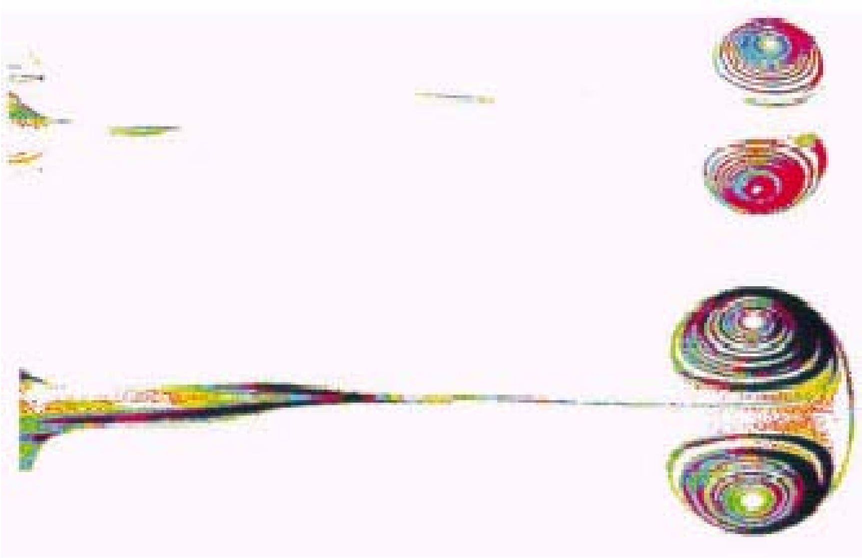

$$L/D = \left[\int_0^t U(\tau)\,d\tau\right] \Big/ D = 2$$

$$L/D = 3.8$$

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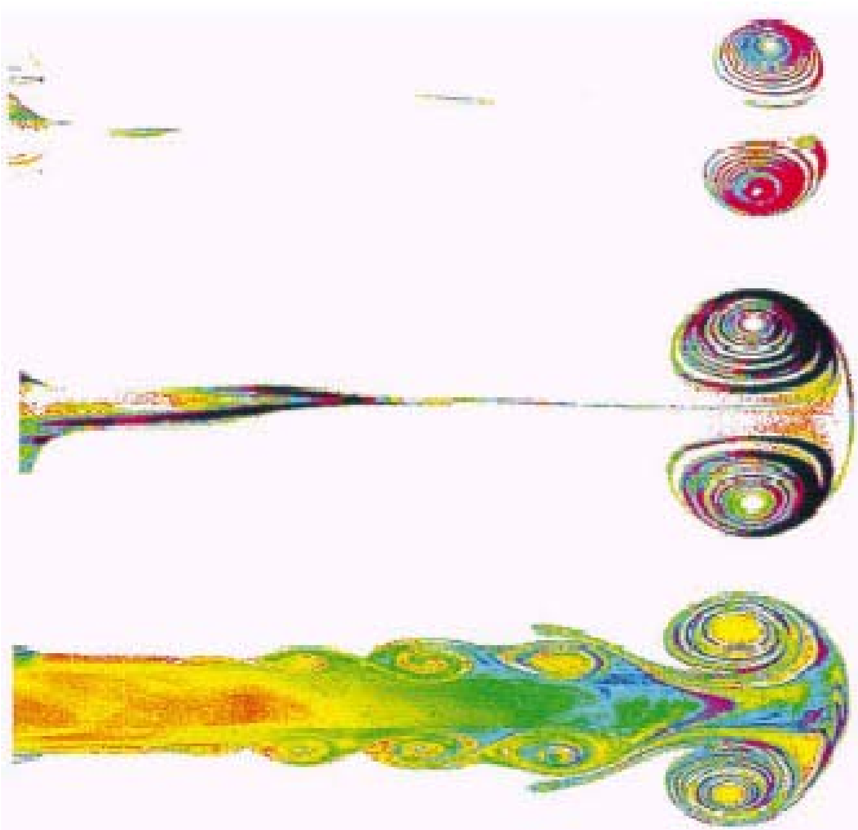

$$\leftarrow \quad L/D = \left[\int_0^t U(\tau)\,d\tau\right] \Big/ D = 2$$

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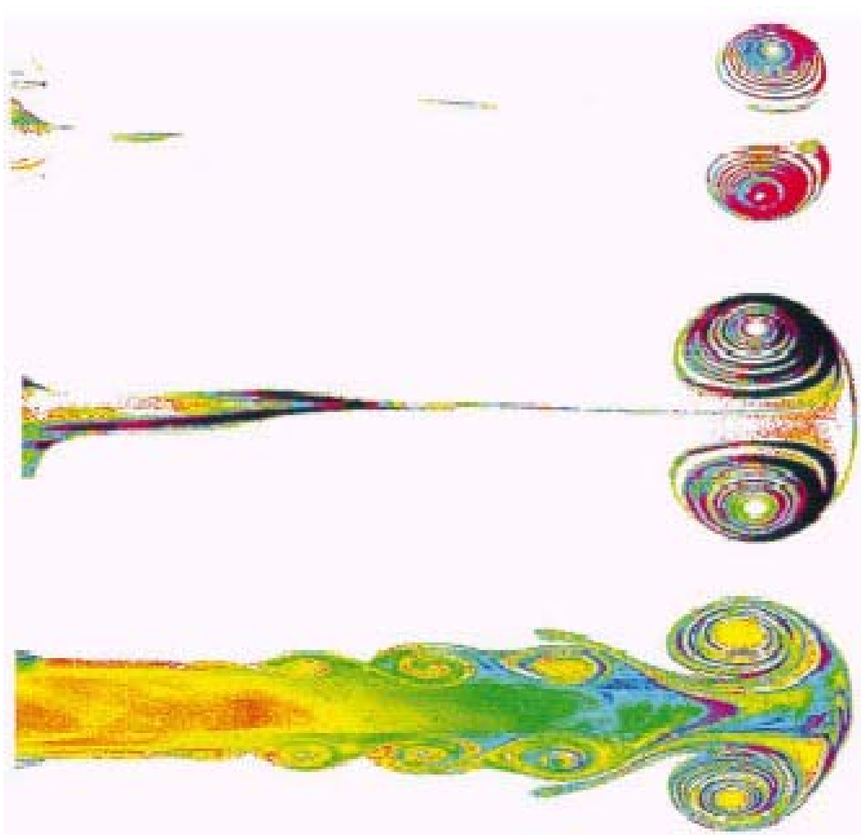


$$L/D = \left[\int_0^t U(\tau)\,d\tau\right] \Big/ D = 2$$

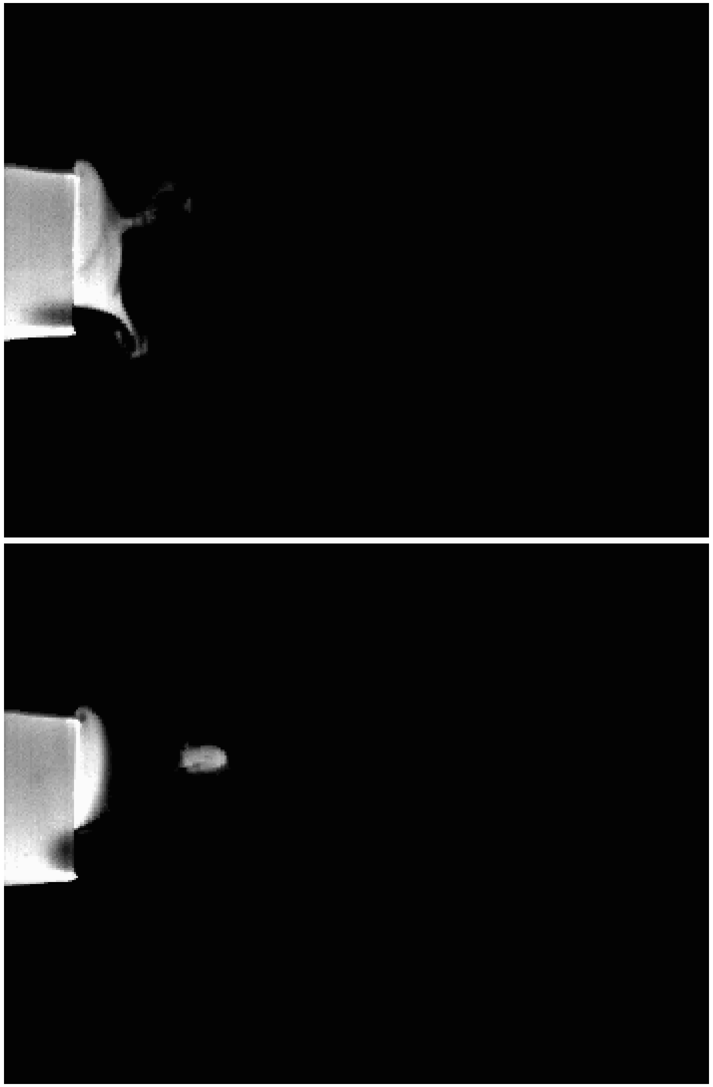
$$L/D = 3.8$$

$$L/D = 14.5$$

$$L/D \approx 4 \equiv \begin{cases} \textbf{Vortex ring formation time} \\ \textbf{Vortex pinch-off time} \end{cases}$$

M. Gharib, E. Rambod & K. Shariff, *Journal of Fluid Mechanics* (1998)

L/D = 2 vs. 4



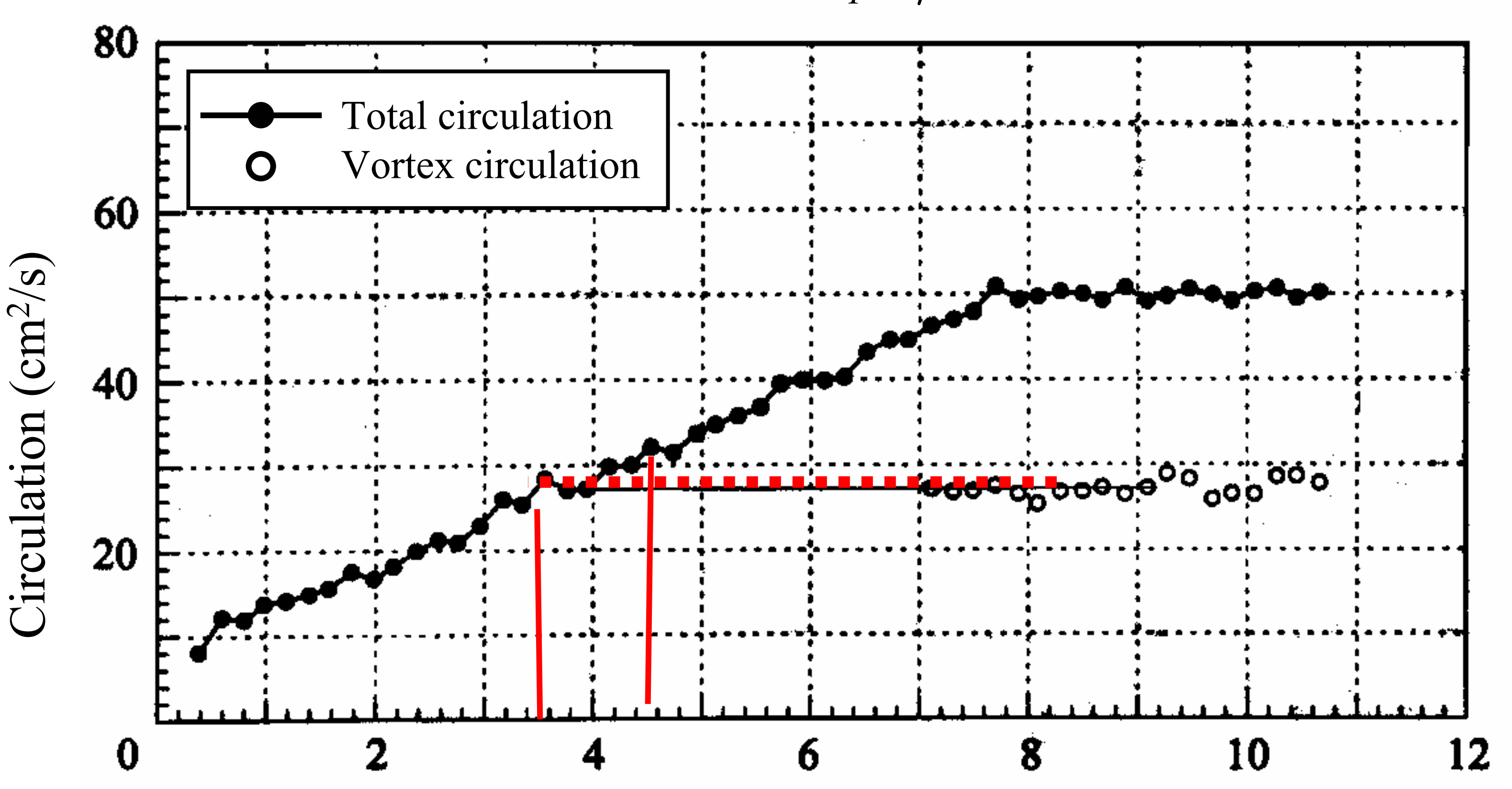
L/D = 2

L/D > 4

P.S. Krueger (2001)

The Formation Number (*F*)

Formation Time $\leftrightarrow \overline{U}_p t / D = L / D$

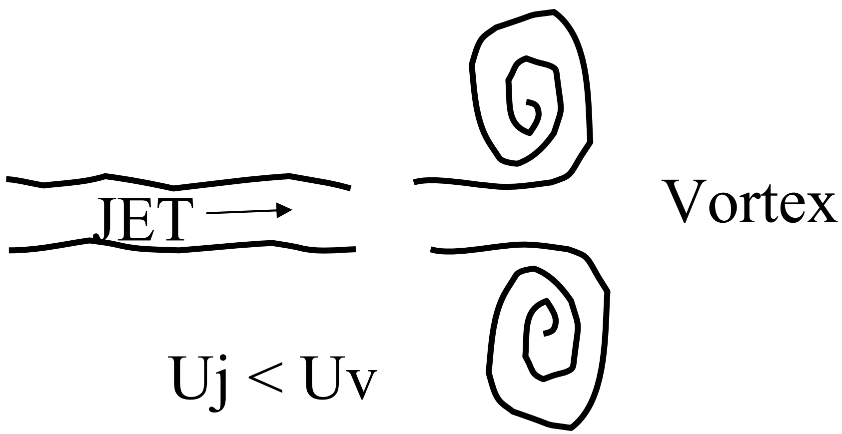


M. Gharib, E. Rambod & K. Shariff, *Journal of Fluid Mechanics* (1998)

Models for Vortex Ring Pinch-off

- Gharib *et al*. (1998): invokes Kelvin-Benjamin Variational principle

Vortex ring pinch off "…occurs when the source energy falls below that of a steadily translating vortex ring"



M. Shusser and M. Gharib, *Physics of Fluids* (2000)

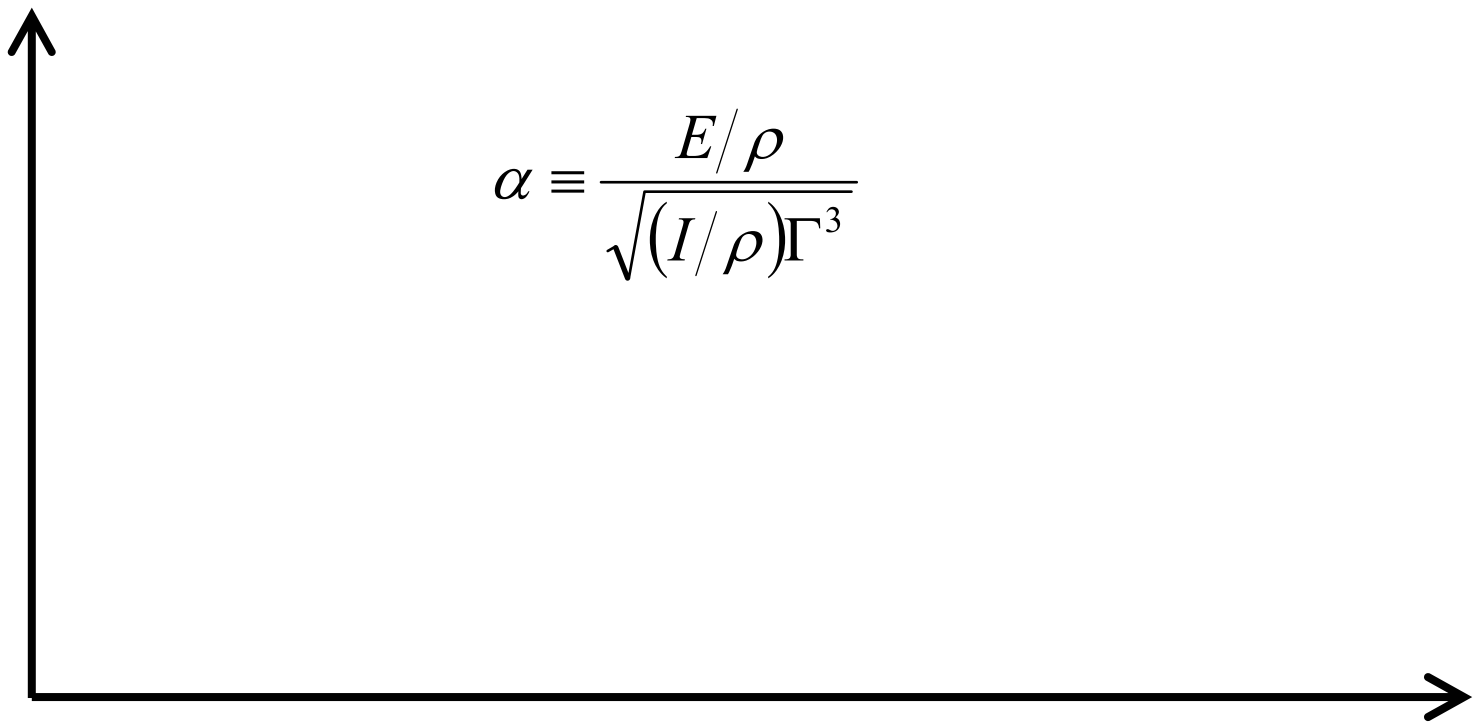
Vortex ring growth is limited by energy effects

For vortex ring growth: vortex generator energy > vortex ring energy

(W.T. Kelvin, 1875; T.B. Benjamin 1976)

$$\alpha \equiv \frac{E/\rho}{\sqrt{(I/\rho)\Gamma^3}}$$

dimensionless energy



L/*D*

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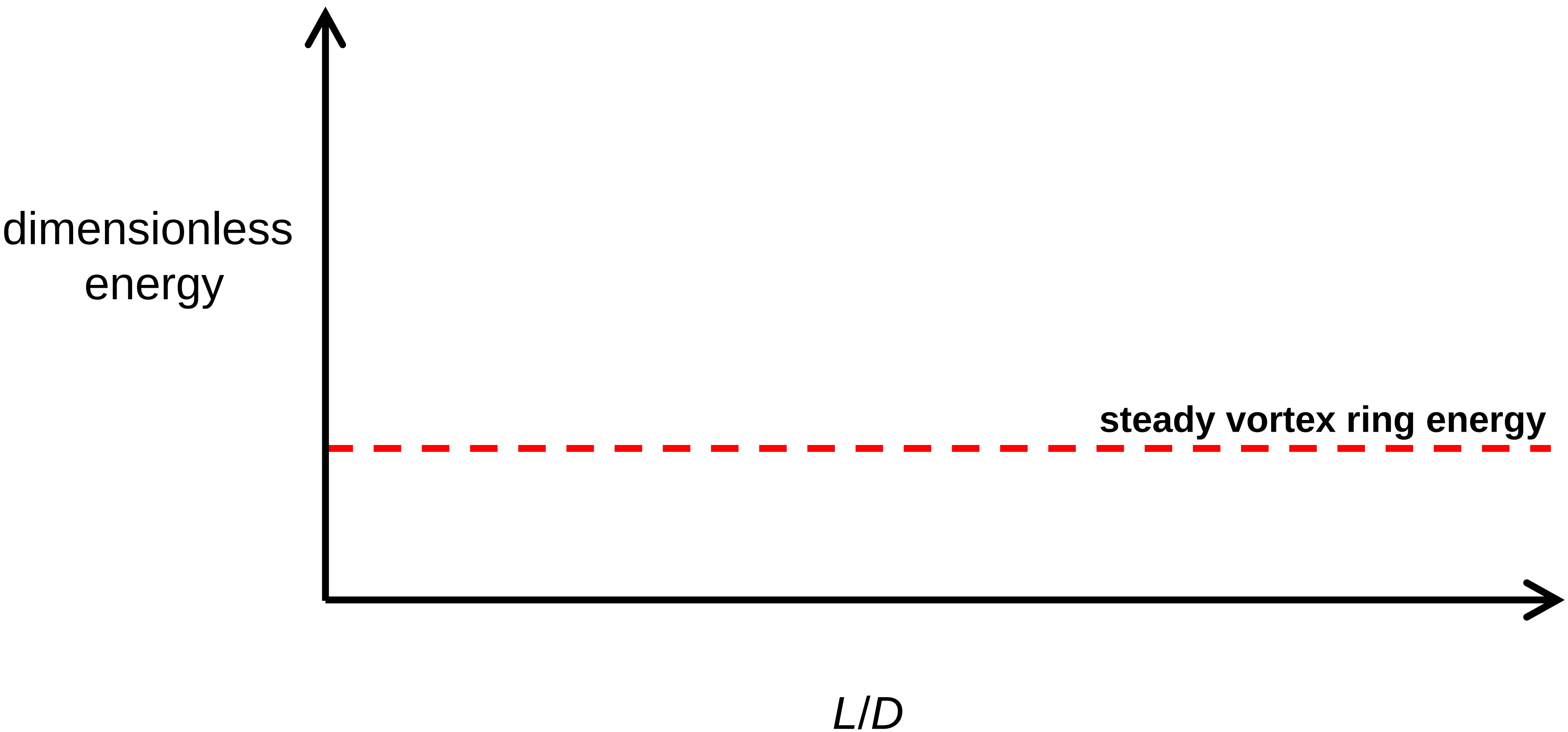

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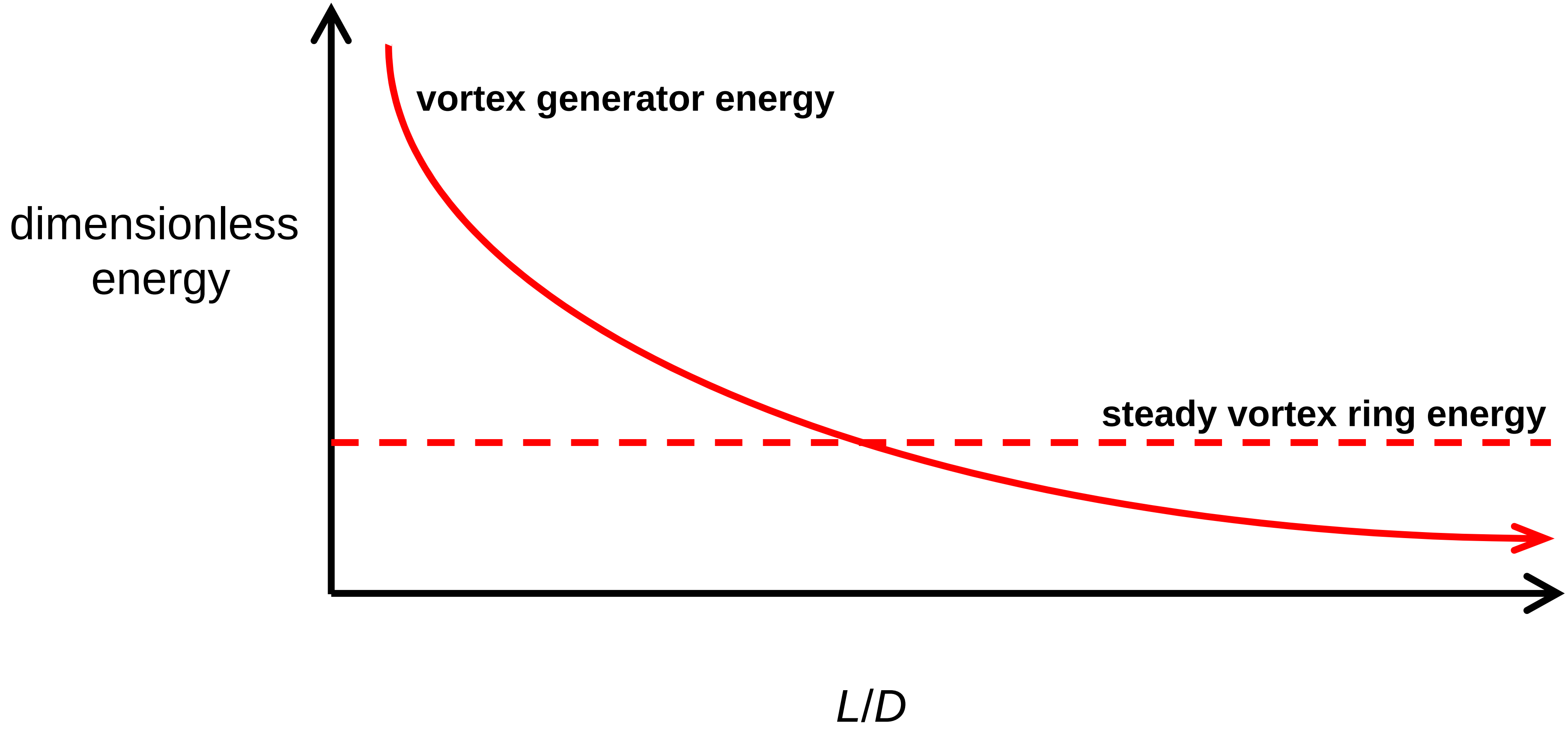

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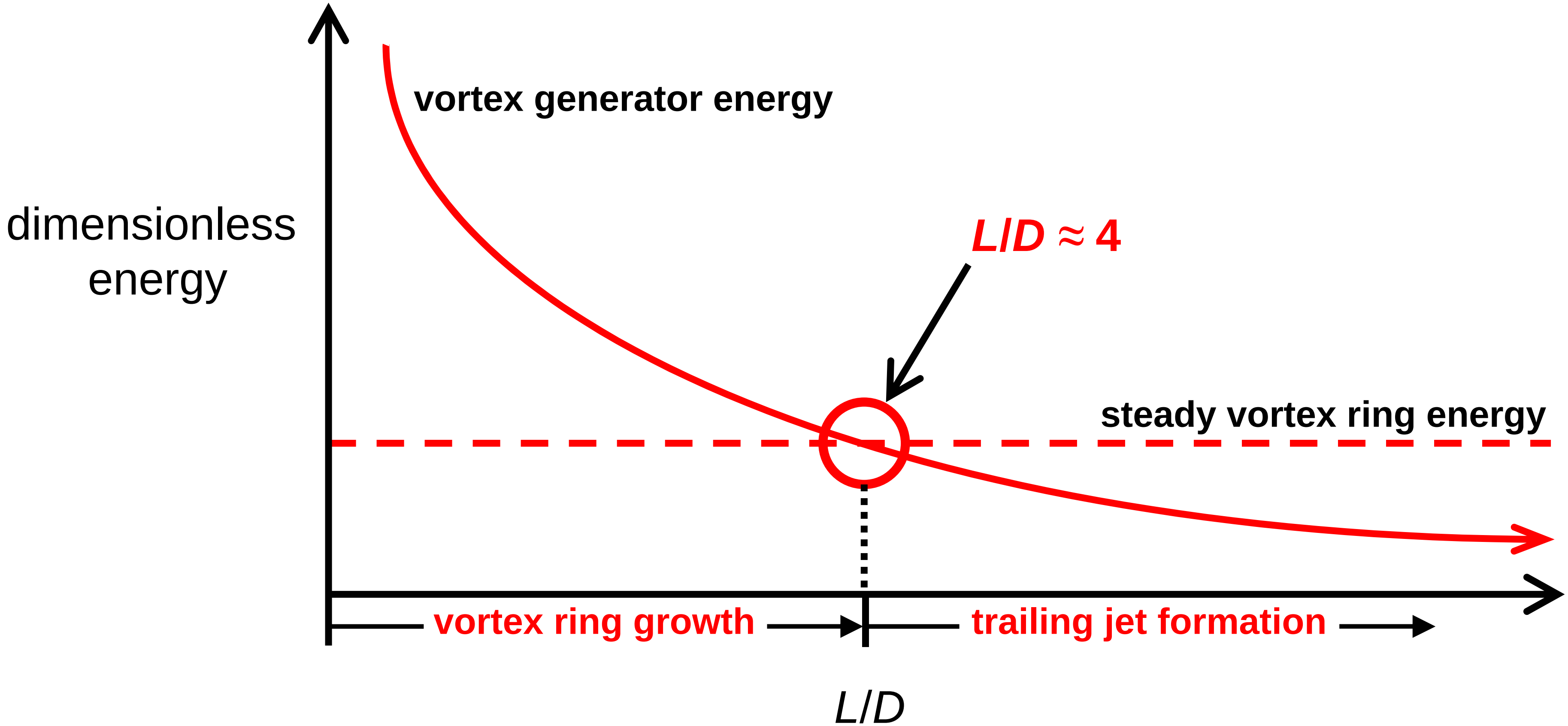

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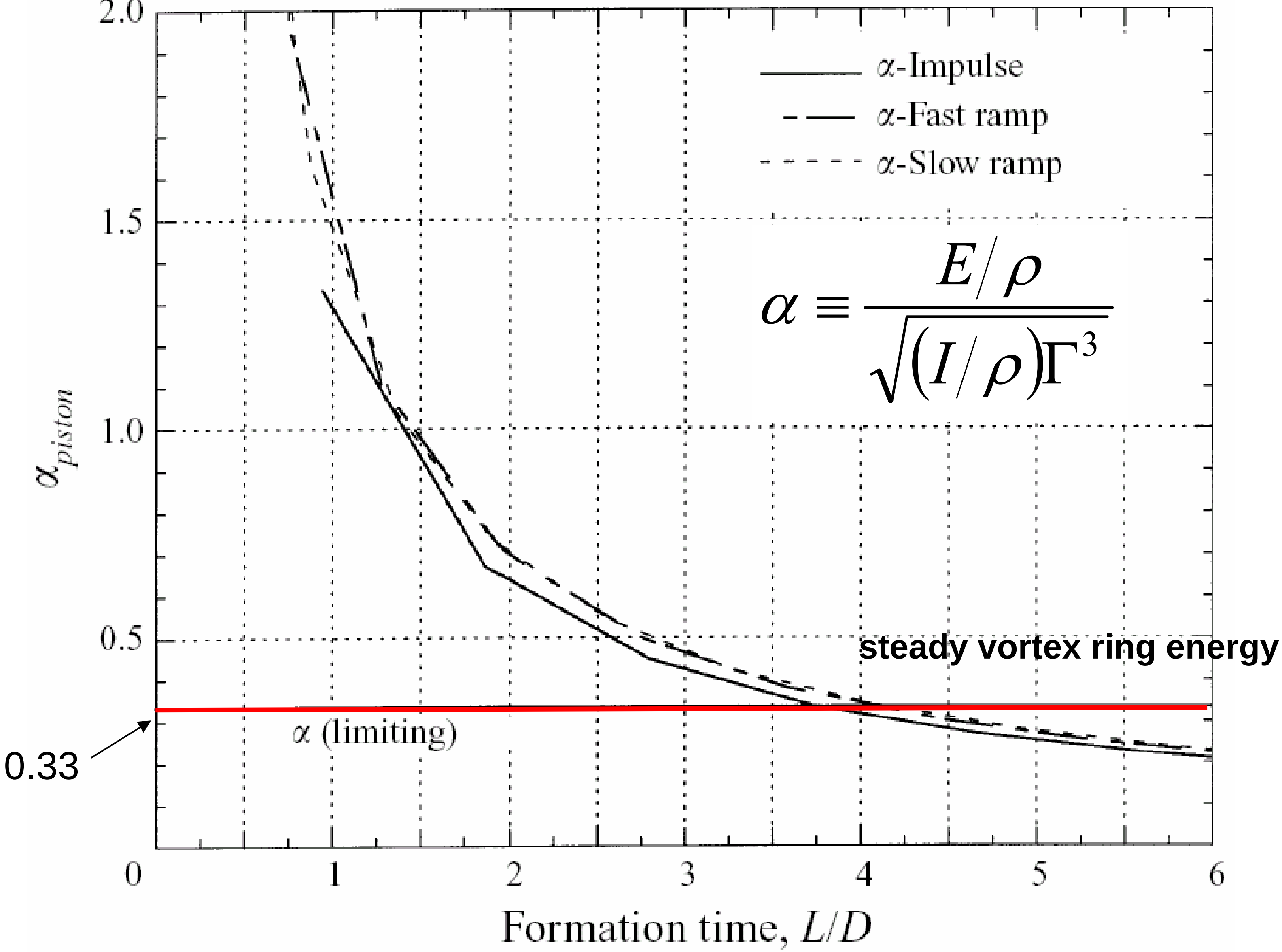
Models for Vortex Ring Pinch-off



M. Gharib, E. Rambod & K. Shariff, *Journal of Fluid Mechanics* (1998)

Models for Vortex Ring Pinch-off

- Mohseni (1998): combines Norbury vortex model and slug model approximation for ring translational velocity

$$U_{vortex} = 0.5 U_{piston}$$

- Linden and Turner (2001): combines Norbury vortex model and volume conservation approximation

$$\Omega_{jet} = \Omega_{vortex}$$

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However, entrained fluid by the leading vortex can reach over 50 percent of its total volume (Ω_{vortex})

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (2004)

Physical Implications of Pinch-Off

Pinch-Off $\Rightarrow$ Maximum vortex ring strength (energy)

$\Rightarrow$ Maximum fluid entrainment per vortex ring and maximum vortex ring velocity

$\Rightarrow$ Maximum thrust per pulse

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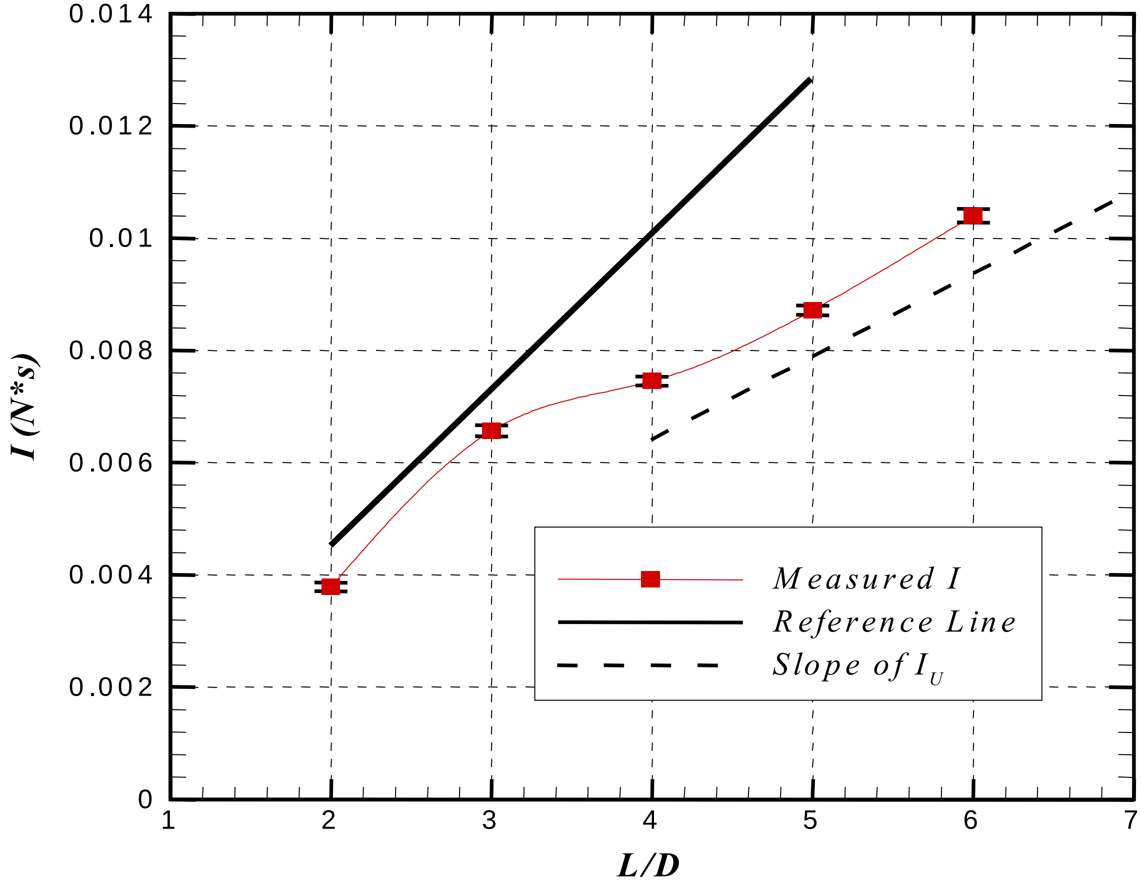
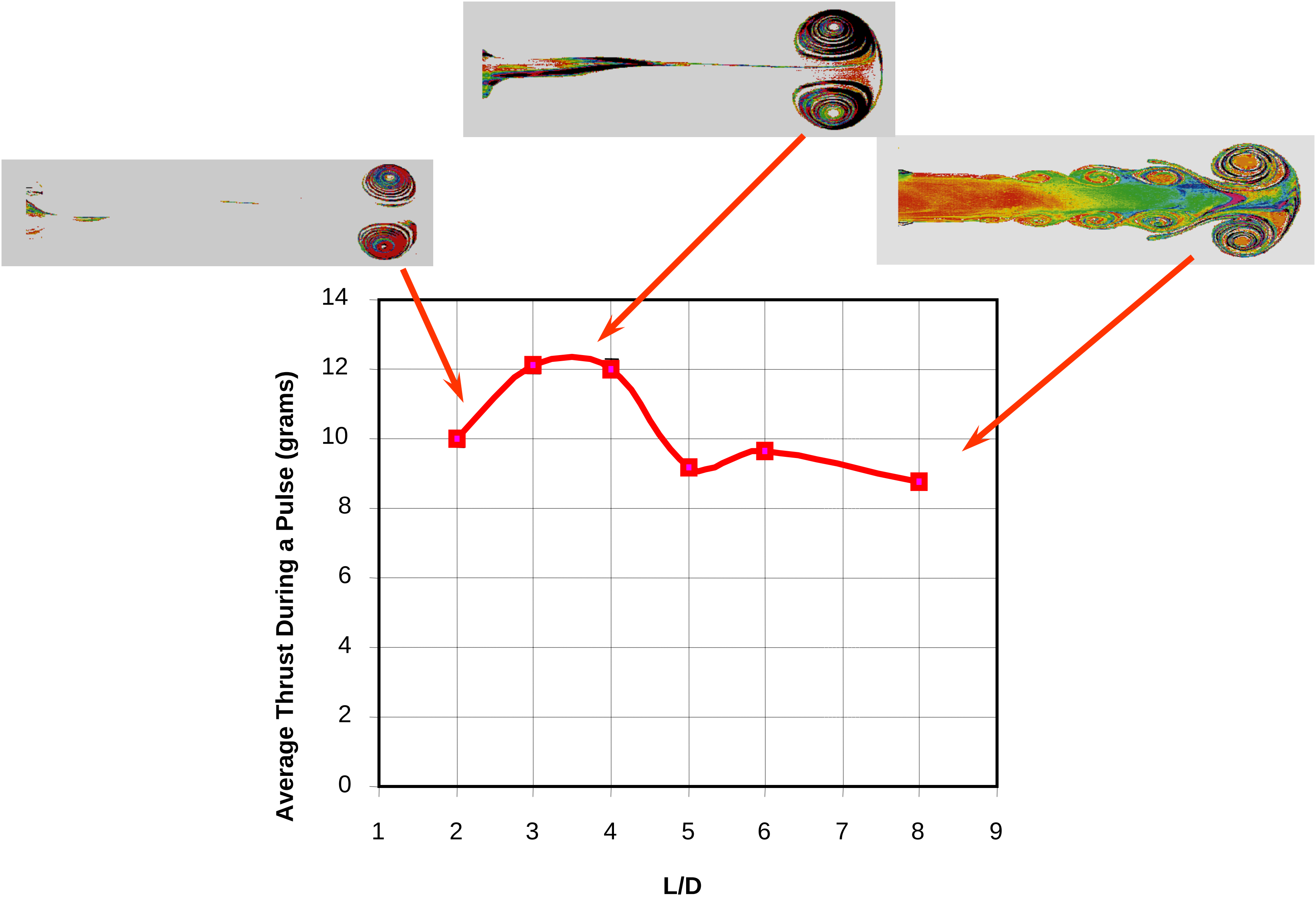
Total Impulse of Starting Jets



$$I_U = I_U\left(t_p\right) \equiv \int_0^{t_p} \int_A u_J^2(r,\tau)\, dA\, d\tau$$

P.S. Krueger and M. Gharib, *Physics of Fluids* (2003)

Average Force of Starting Jets



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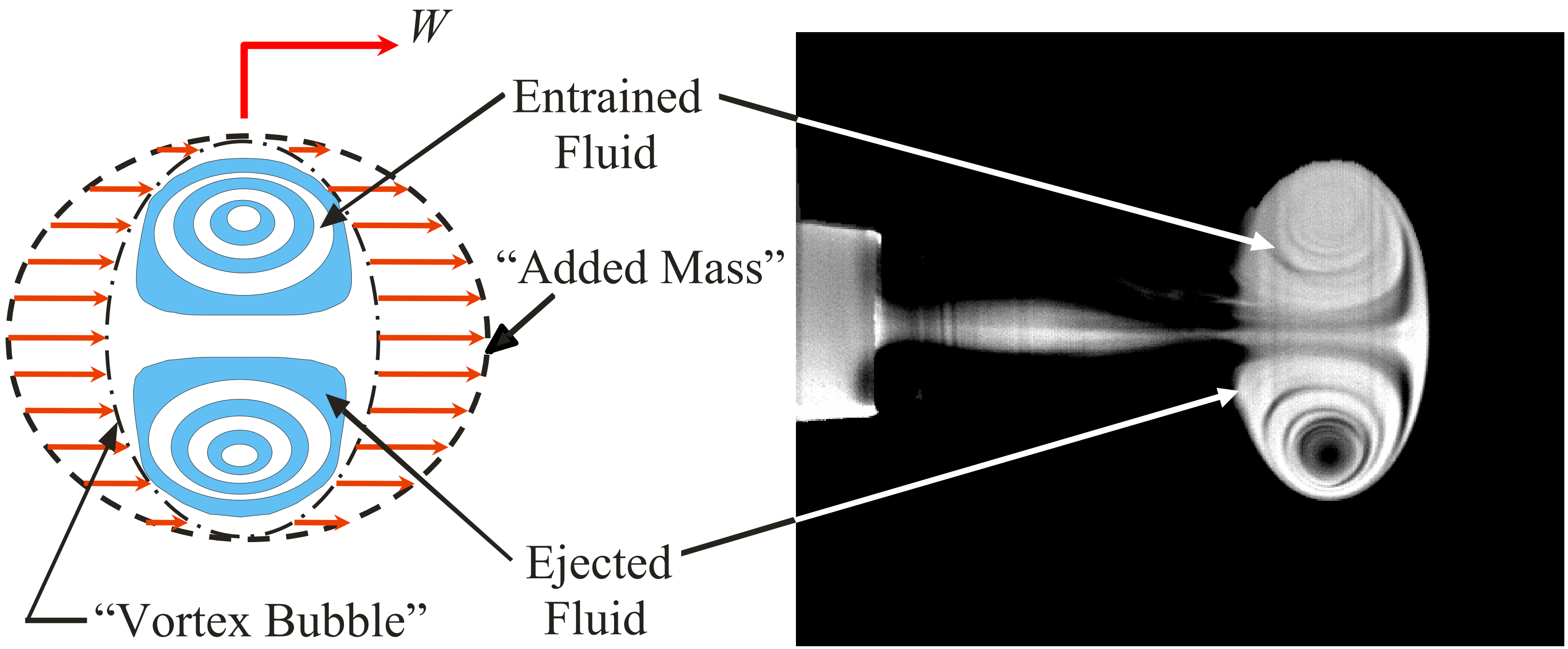
Added and Entrained Mass



[L/D = 2.0, NS Ramp]

$$I_U + I_p = \left(m_{ejected} + m_{entrained} + m_{added}\right)W$$

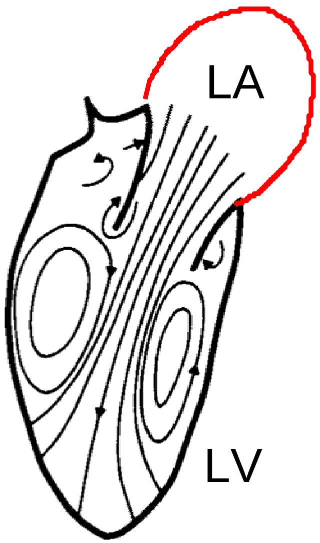
Experiments $\Rightarrow \quad m_{ejected}W < I_U$

P.S. Krueger and M. Gharib, *Physics of Fluids* (2003)

Limiting physical processes dictate "optimal" parameters for vortex ring formation

Experiments demonstrate correlation between vortex ring pinch-off and maximum mass and momentum transfer

Do biological systems exploit vortex ring formation for optimal fluid transport?



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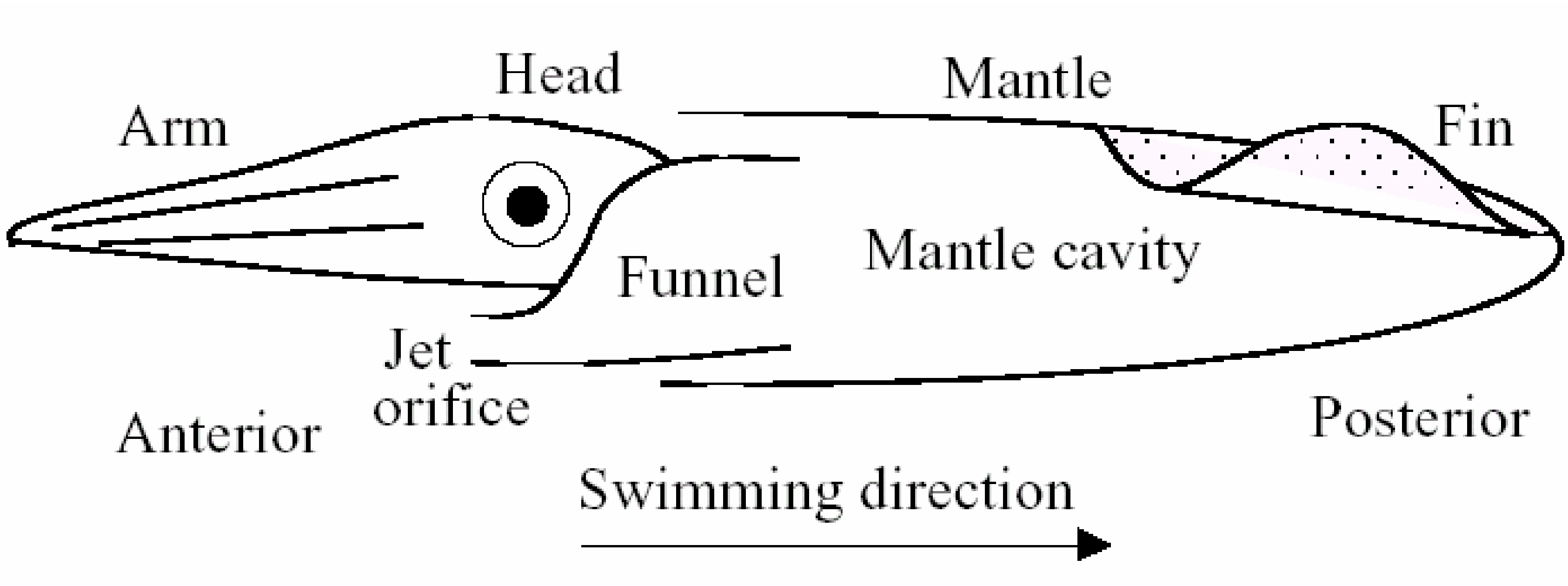
Do biological systems exploit vortex ring formation for optimal fluid transport?

B. Lin and M. Gharib (2003)

J.O. Dabiri et al. (2004)

Previous attempts to verify optimal vortex formation in biological systems have been inconclusive



$$L/D \rightarrow L/\overline{D} \text{ where } \overline{D} = \frac{1}{t}\int_0^t D(\tau)\,d\tau$$

I.K. Bartol et al., *Journal of Experimental Biology* (2001)

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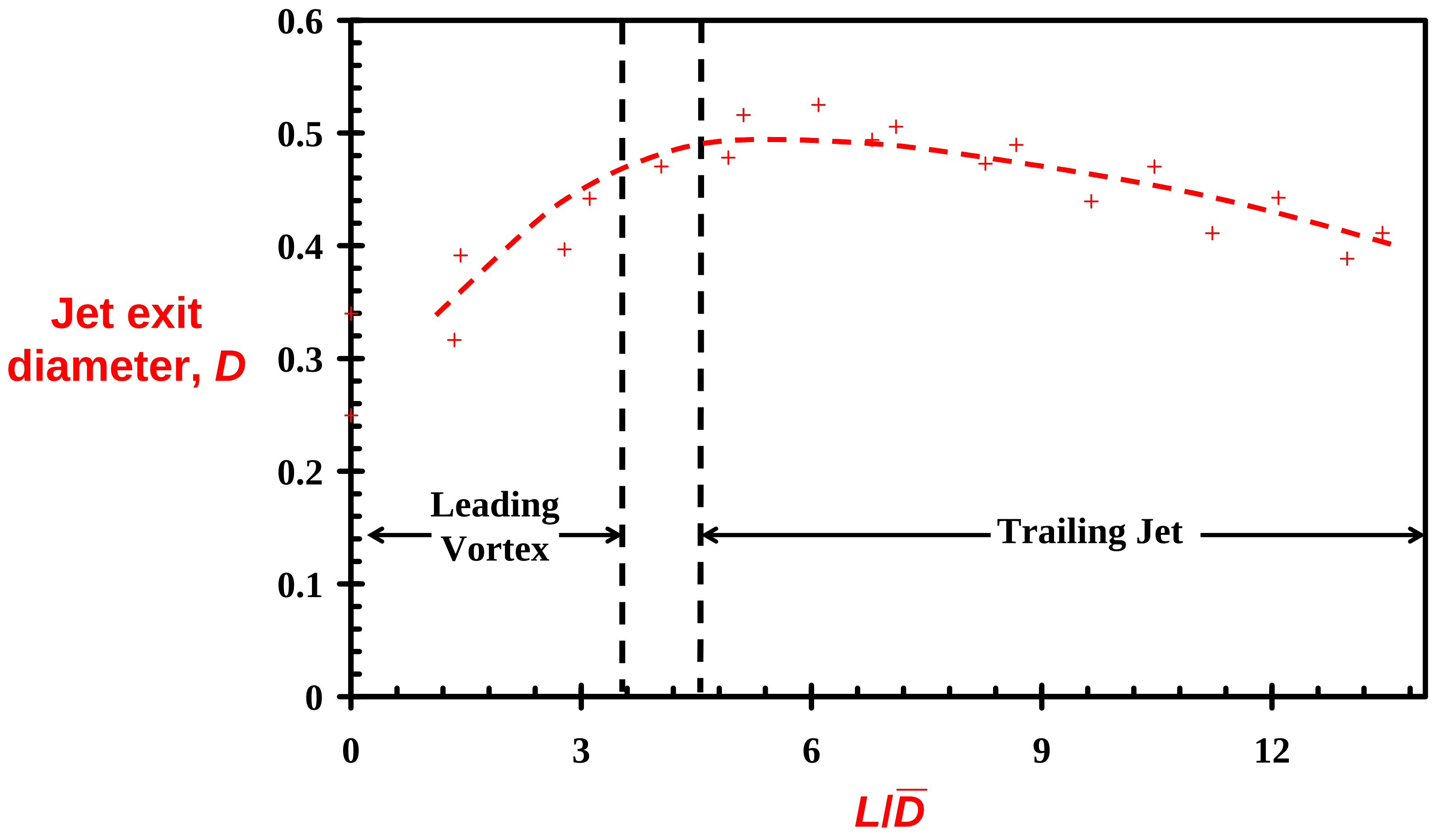

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Measurements in the literature…

Squid: $L/\overline{D}$ = 4-7, 10-40, 34, **87**

Salps: $L/\overline{D}$ = 3-4, 6.7, 10-20

Jellyfish: $L/\overline{D}$ = **0.2**-4.4

Are we missing something?

Biological Factors Affecting Pinch-off

- Co-flow

  Swimming and flying animals generate vortices in a free-stream flow

Biological Factors Affecting Pinch-off

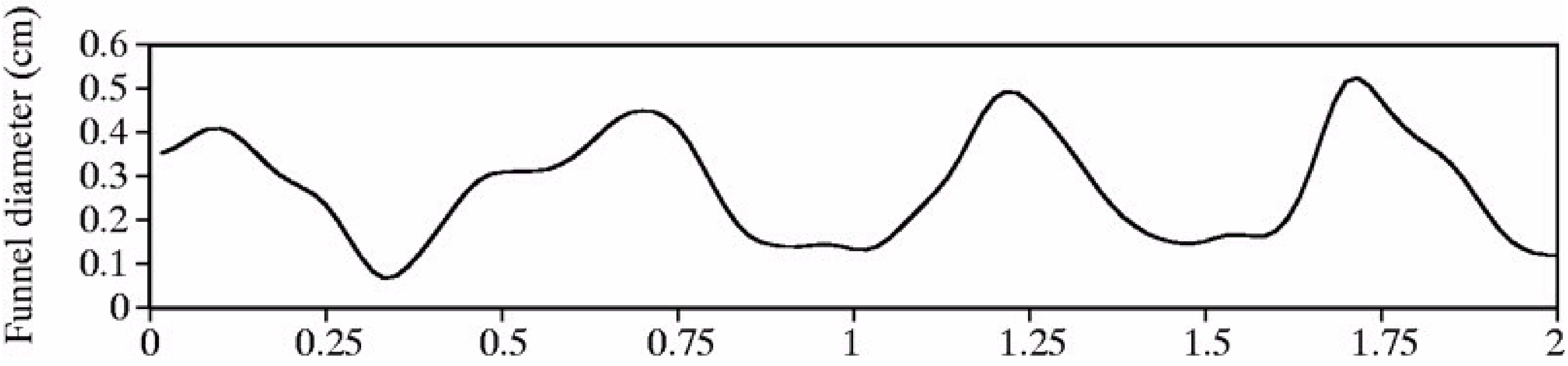
- Co-flow

  Swimming and flying animals generate vortices in a free-stream flow

- Temporal exit diameter variation

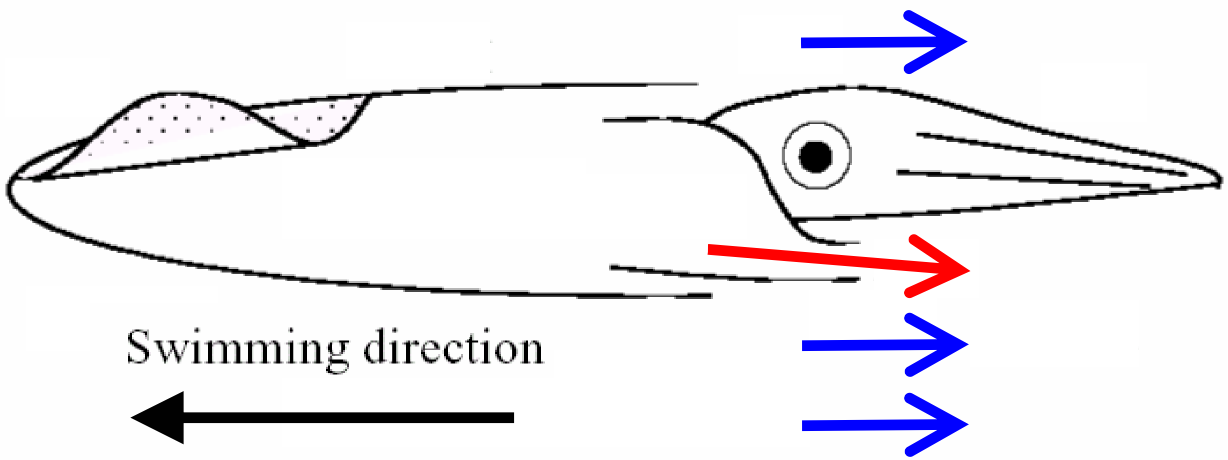
  e.g. squid (Bartol *et al.*, 2001)

  Parallels time-dependent flap kinematics in other locomotion modes



A proper analysis must include *fluid-structure interactions*

External interactions: Flow past the vortex generator



Flow past the propulsor can affect vortex ring formation

P.S. Krueger, J.O. Dabiri and M. Gharib, *Physics of Fluids* (2003)

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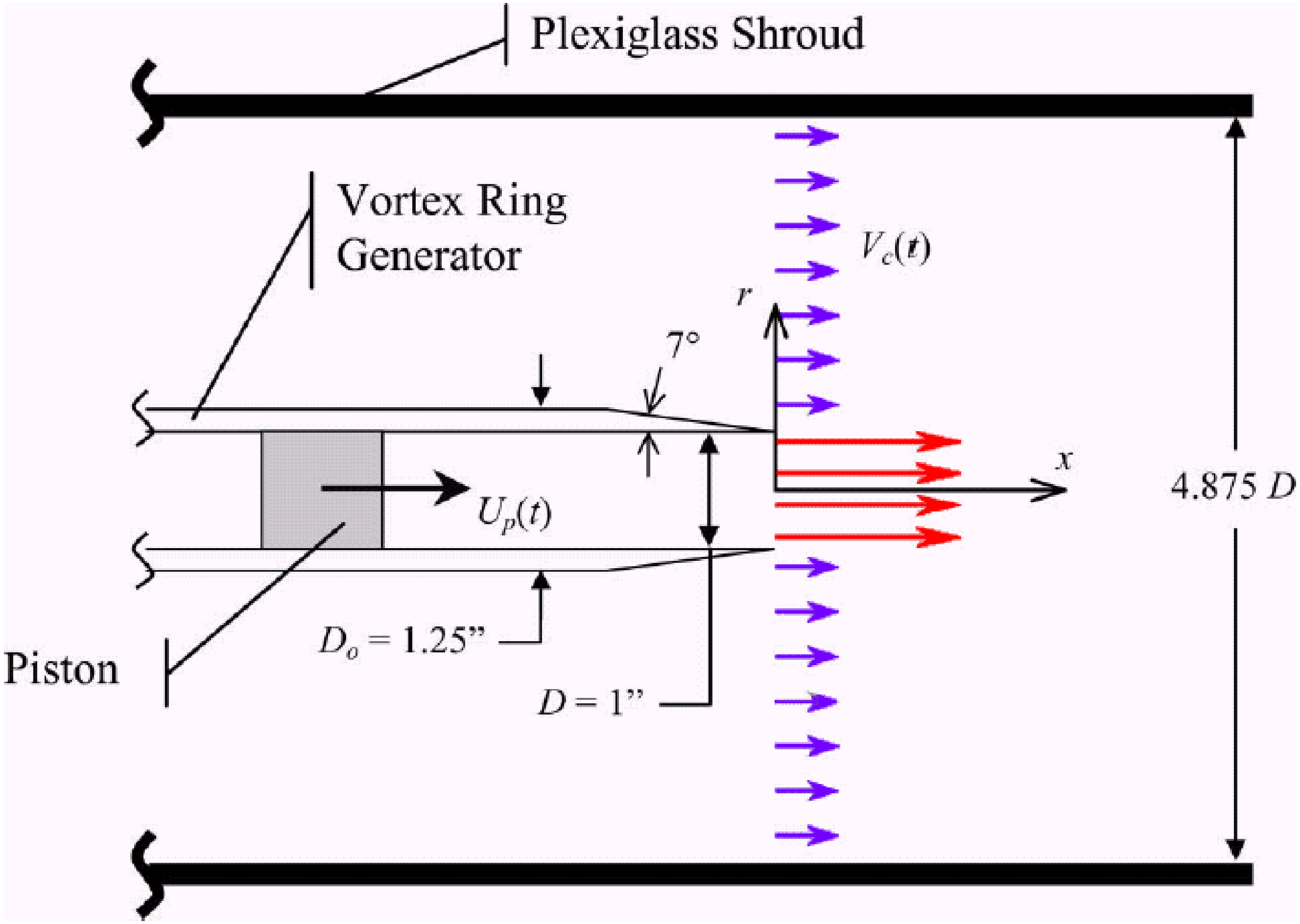

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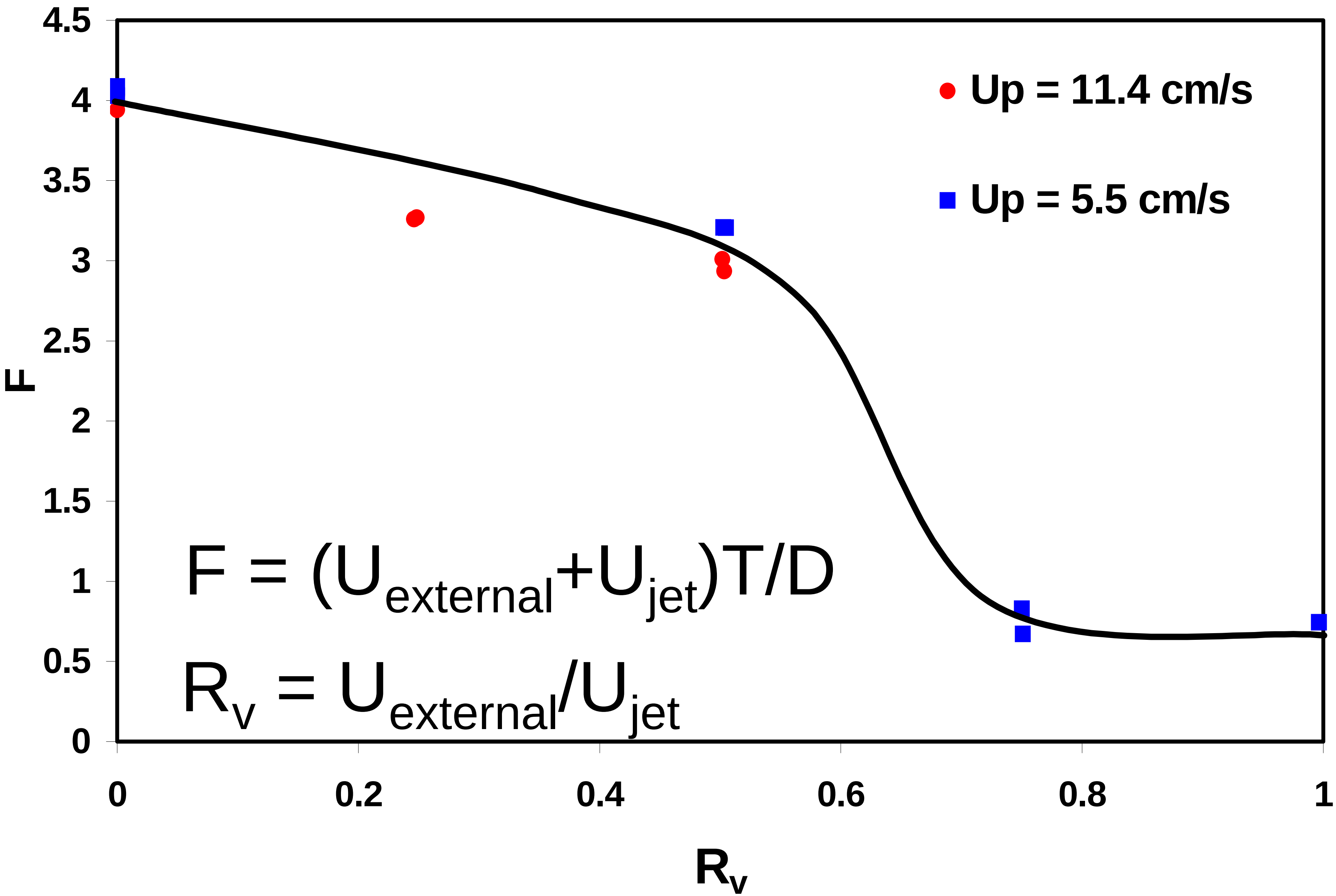
Effects of Co-flow



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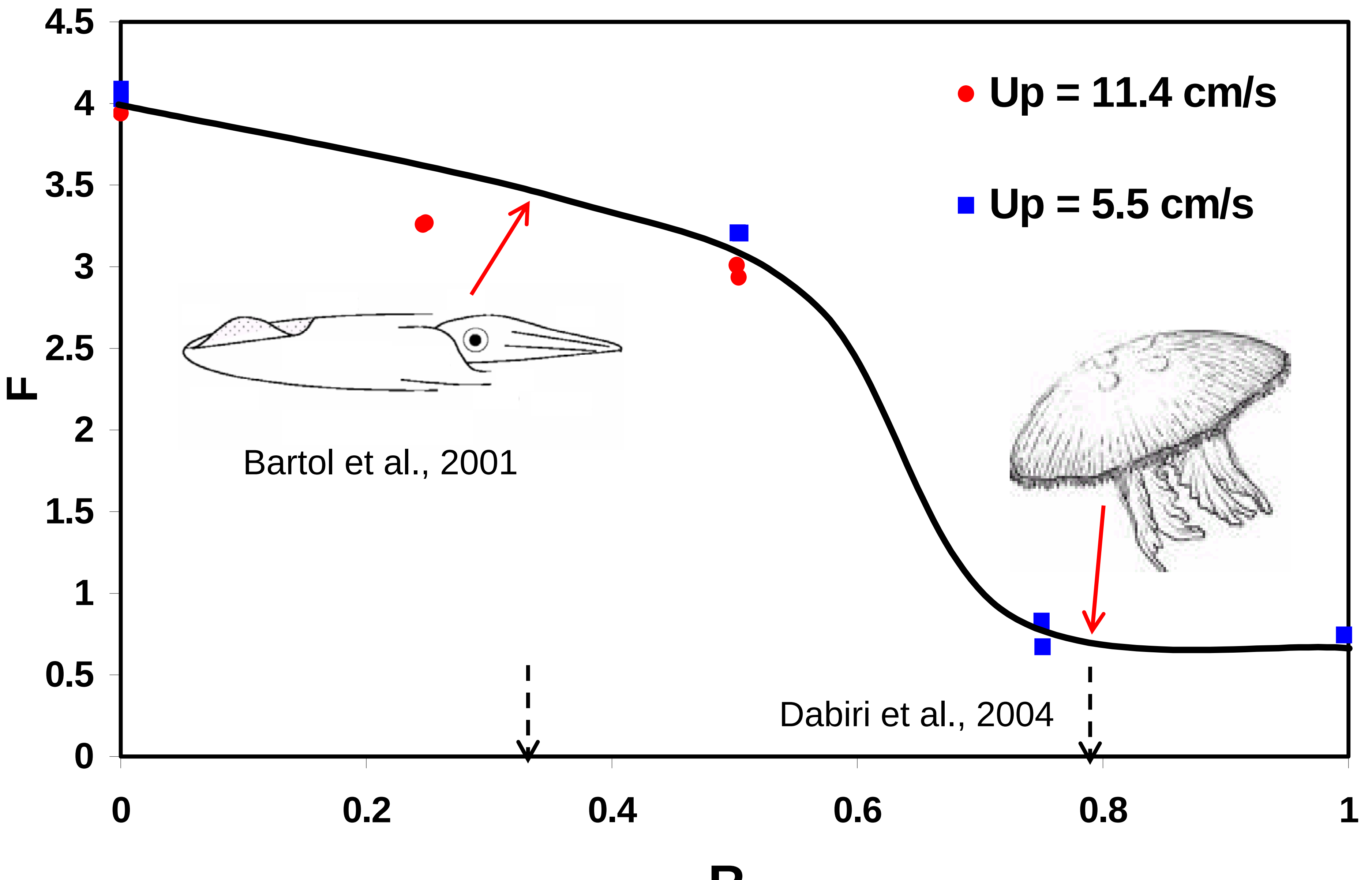
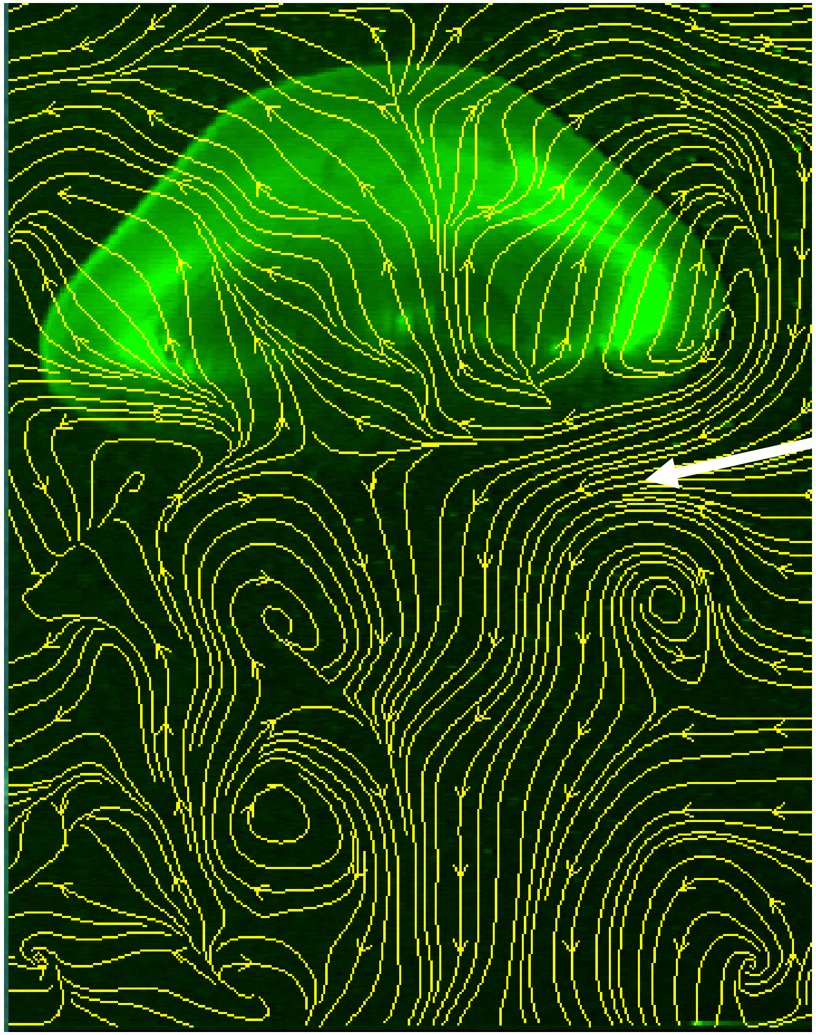


Effects of Co-flow

Animals can exploit external flow in other flow-related functions (i.e. feeding and maneuvering)

See Gallery of Fluid Motion Video #14 (Dabiri et al.)



feeding via vortex ring fluid entrainment

A proper analysis must include
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Internal interactions: Dynamical effects of a variable exit $D(t)$

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

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Internal interactions: Dynamical effects of a variable exit *D*(*t*)

Possible effects

1) As a source of additional vorticity

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

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1) As a source of additional vorticity

2) As a manipulator of existing vorticity

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Internal interactions: Dynamical effects of a variable exit $D(t)$

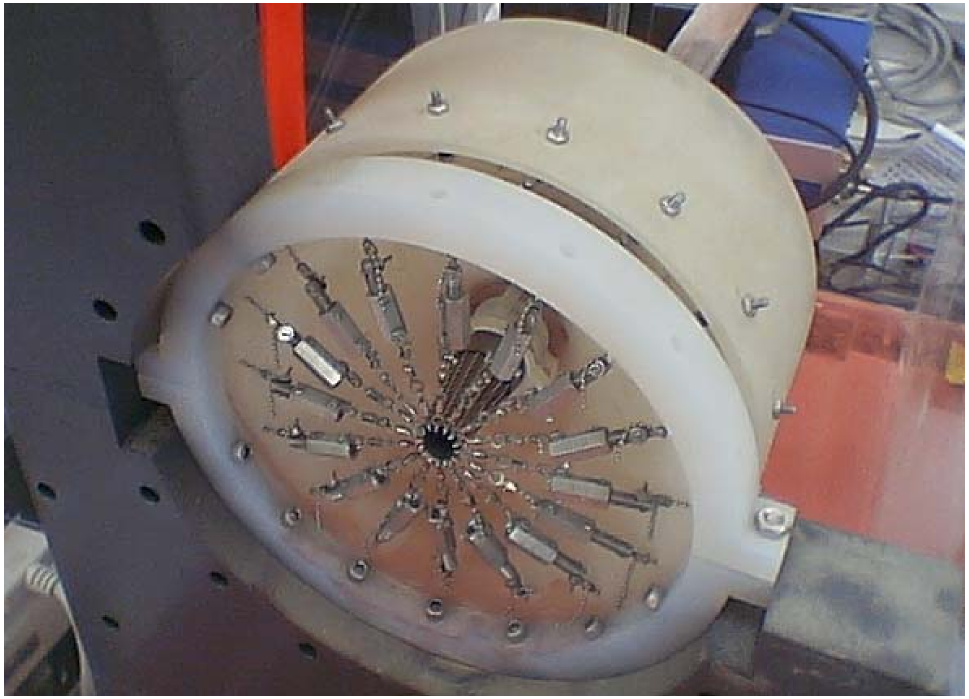
Possible effects

1) As a source of additional vorticity
2) As a manipulator of existing vorticity

These effects are obscured when the time-dependent $D(t)$ is replaced by $\overline{D}$

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

A new technique replicates fluid-structure interactions in variable-diameter jet flows



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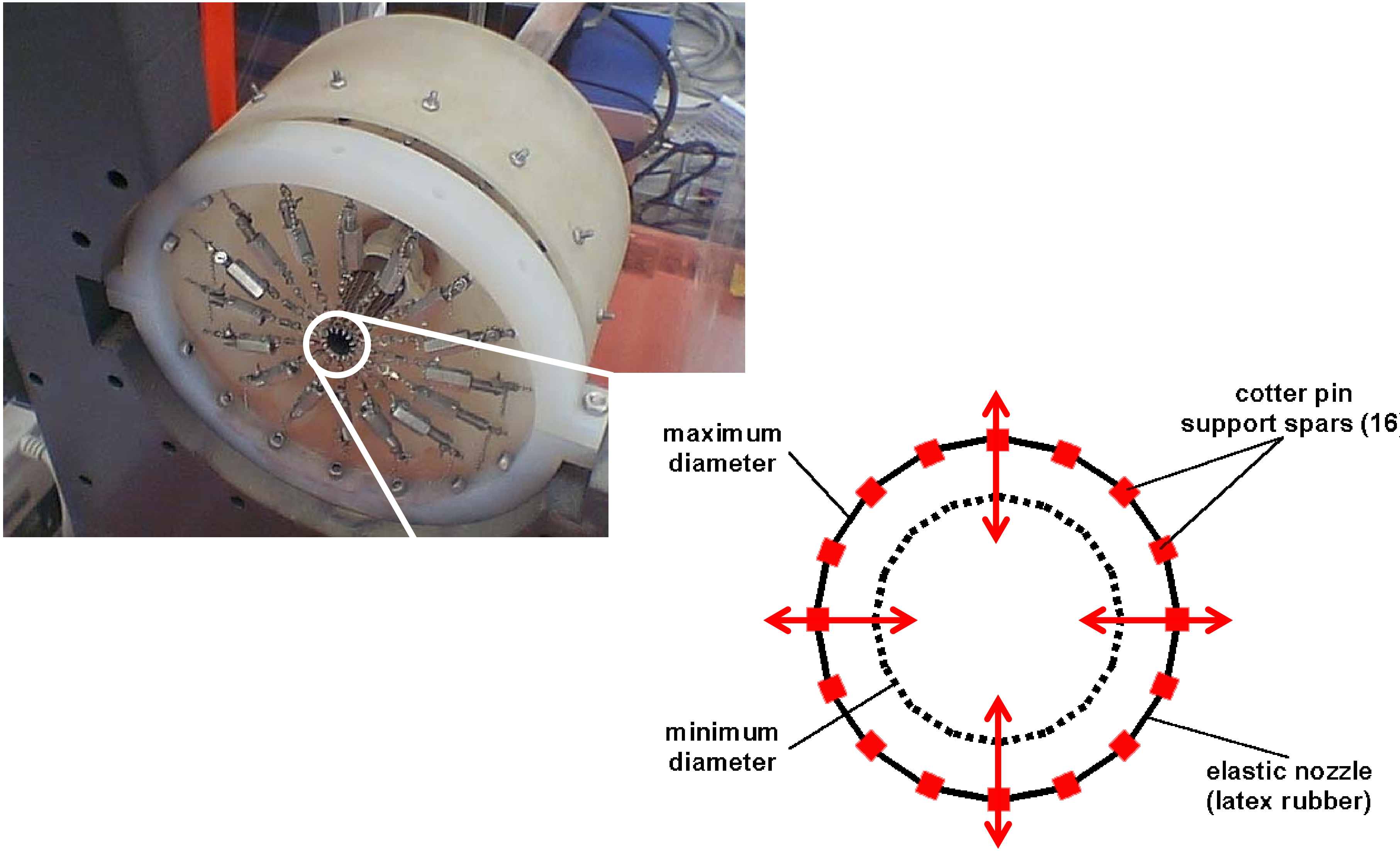

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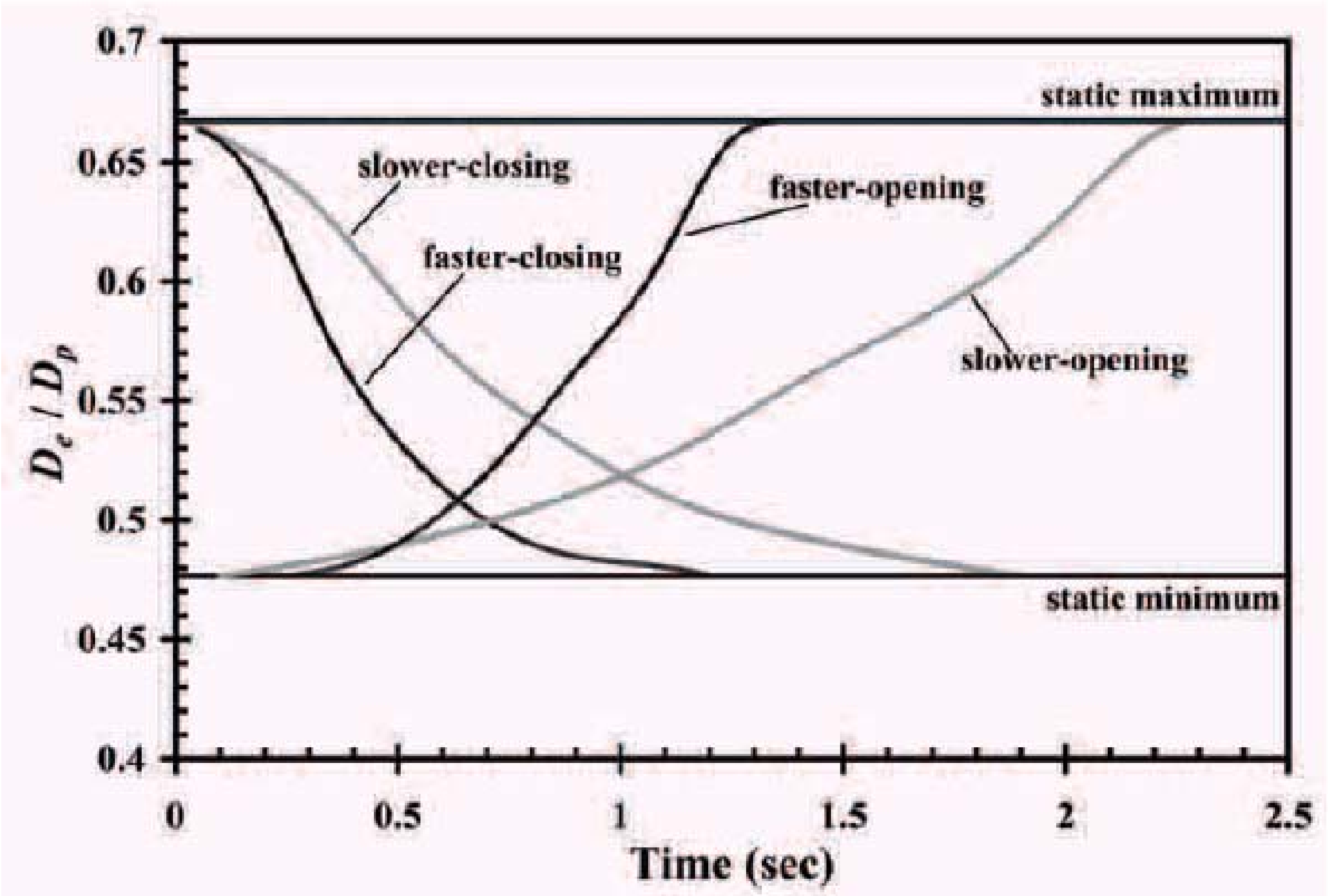

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

A new index for vortex formation properly accounts for time-dependent boundary conditions

"DYNAMIC FORMATION TIME"

Increase the vortex formation time incrementally:

$$\Delta\left(L/D\right)^{*} \equiv \left(\mathbf{U}\left(\tau\right)/\mathbf{D}\left(\tau\right)\right)\Delta\tau$$

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Integrating from flow initiation at $\tau = 0$ to flow termination at $\tau = t$:

$$\left(\boldsymbol{L}/\boldsymbol{D}\right)^{*} = \int_{0}^{\boldsymbol{t}} \left(\mathbf{U}\left(\boldsymbol{\tau}\right)/\mathbf{D}\left(\boldsymbol{\tau}\right)\right)\mathbf{d}\boldsymbol{\tau}$$

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

Nondimensional Analysis

- Normalized Circulation

$$\Gamma^* = \frac{\overline{\Gamma\left(U_e / D_e\right)}}{\overline{U_e^2}}$$

- Normalized Time

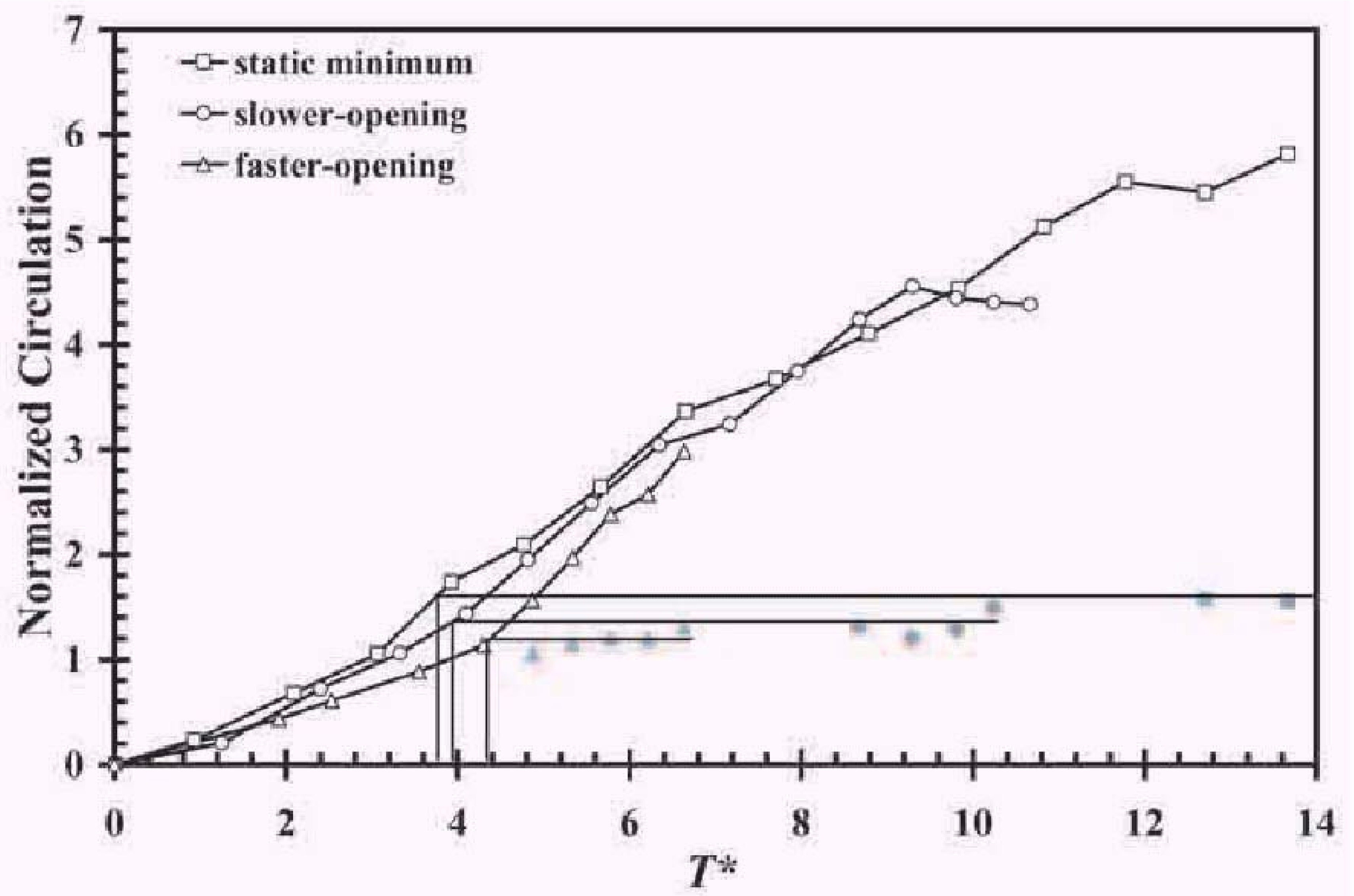
$$T^* = \int_0^t \frac{U_e(\tau)}{D_e(\tau)} d\tau = \overline{\left(\frac{U_e}{D_e}\right)} t$$

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

Vortex formation time is unaffected by *temporal increases in jet diameter*

- $(L/D)^* = 4.0 \pm 0.5$ for all $dD(t)/dt > 0$ tested

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)



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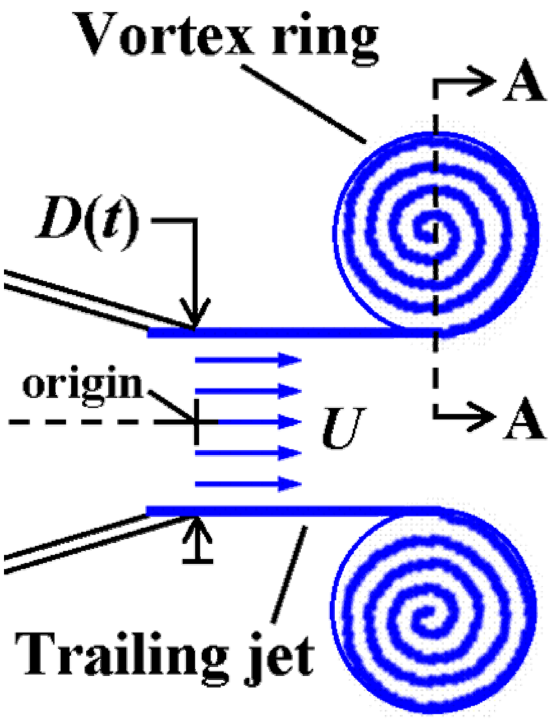

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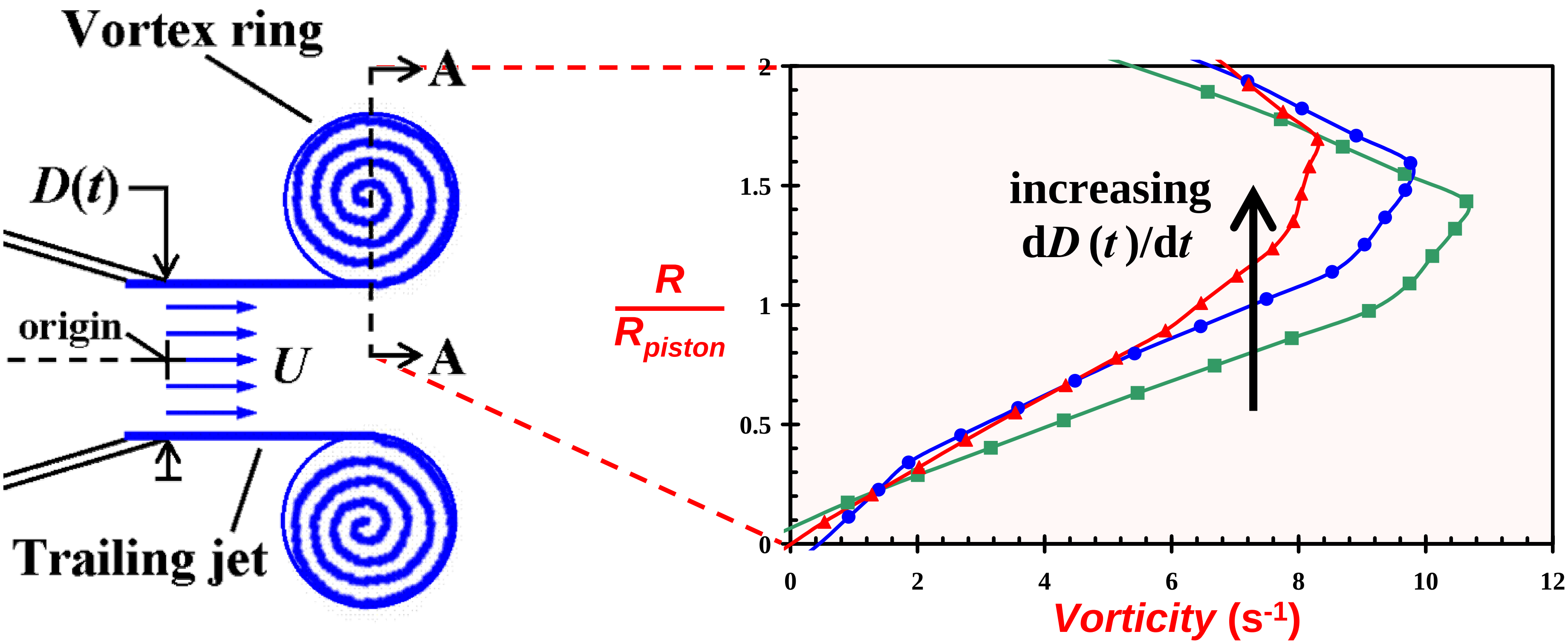

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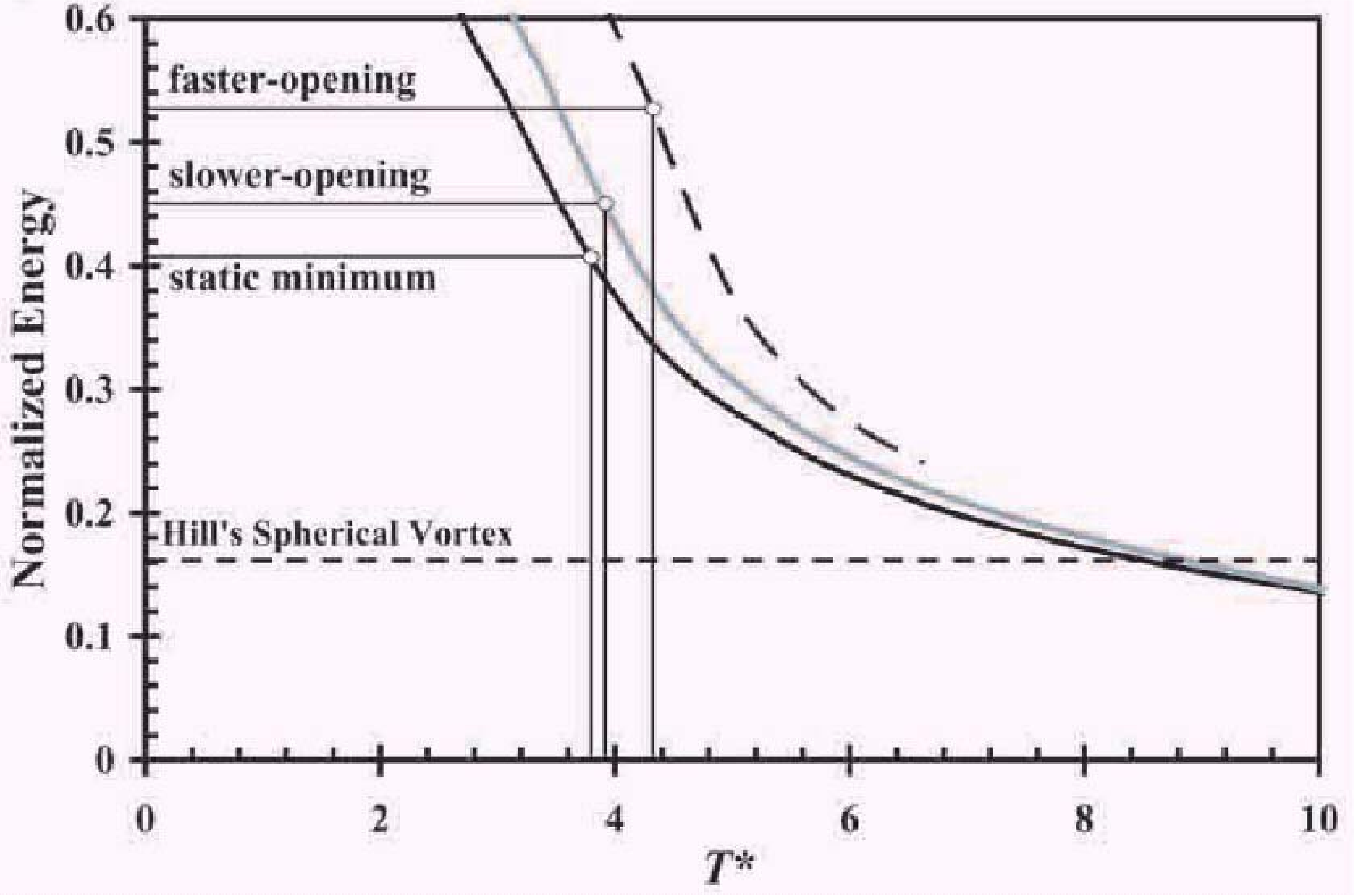

J.O. Dabiri and M. Gharib, *Journal of Fluid Mechanics* (to appear)

These results suggest the first set of *engineering strategies for optimal fluid transport*

During fluid ejection at (*L*/*D*)* < 4:

$$I_{(L/D)^*<4} \sim D^2$$

(J.O. Dabiri & M. Gharib, *J Fluid Mech*)

J.O. Dabiri and M. Gharib, *Proceedings of the Royal Society B* (submitted)

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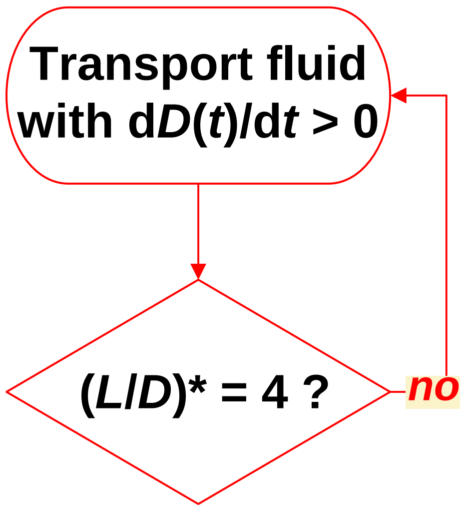

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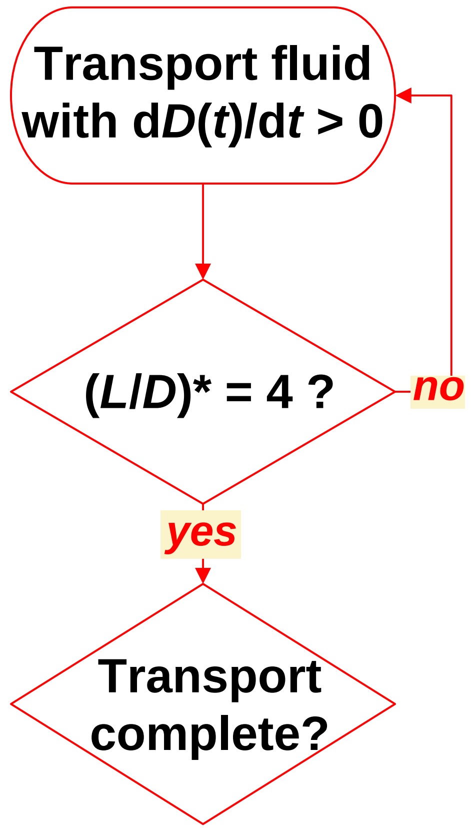

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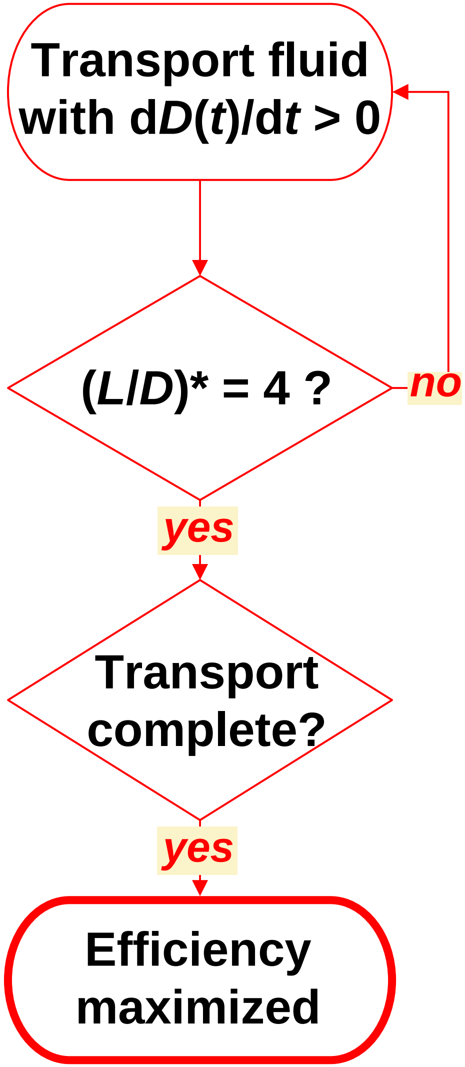

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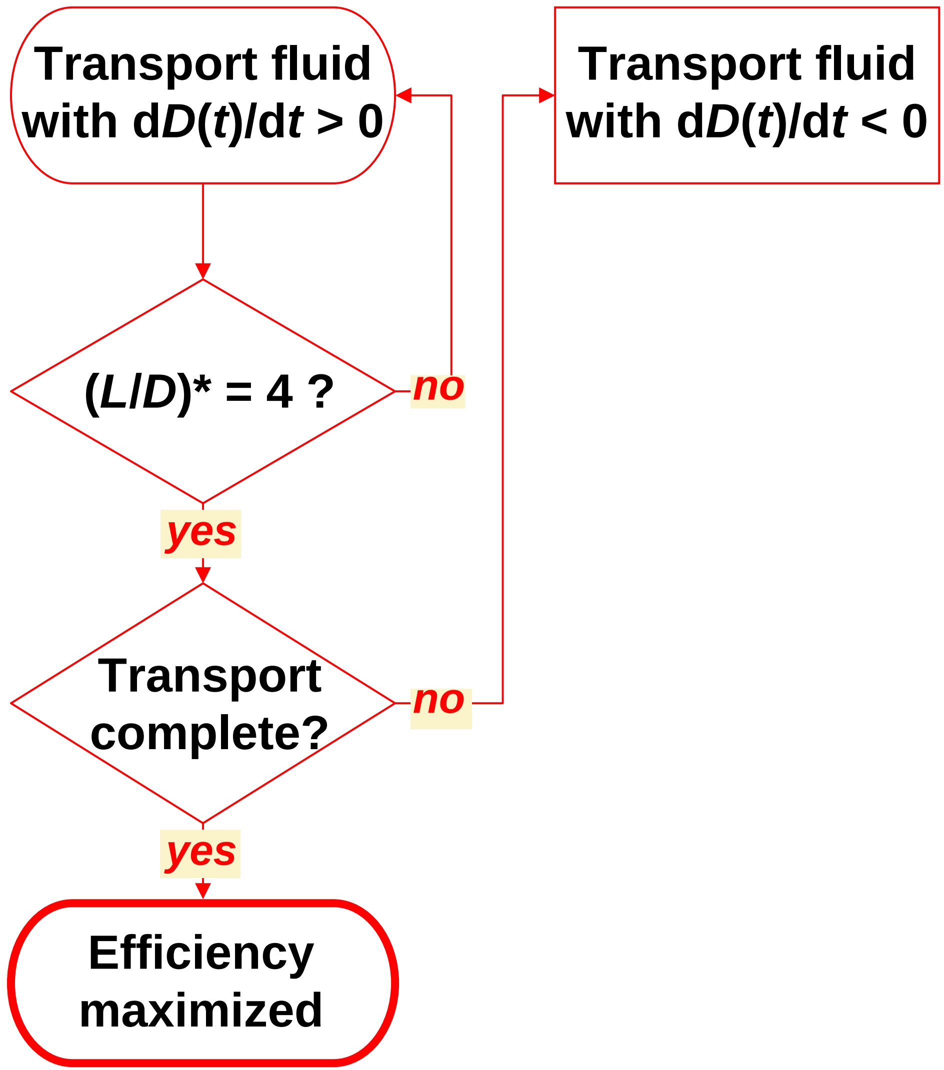

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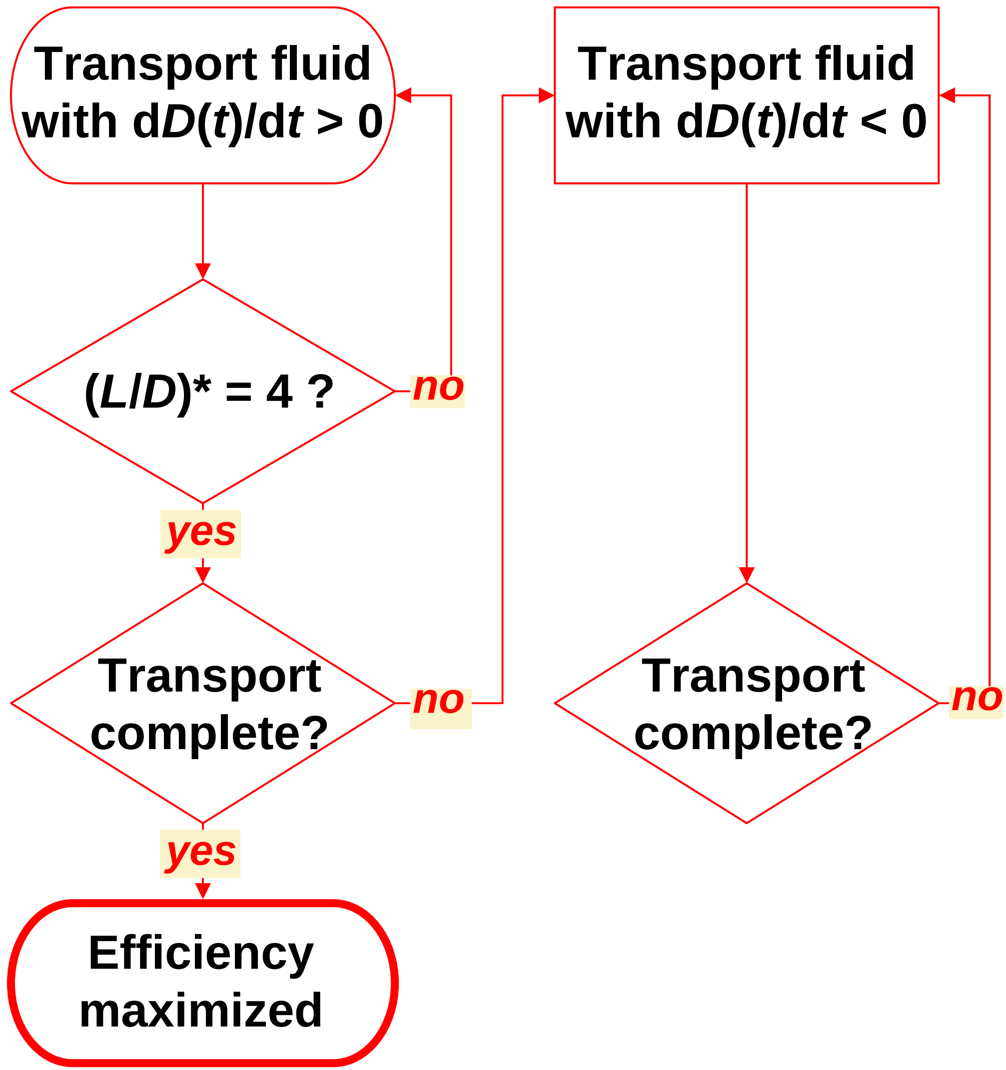

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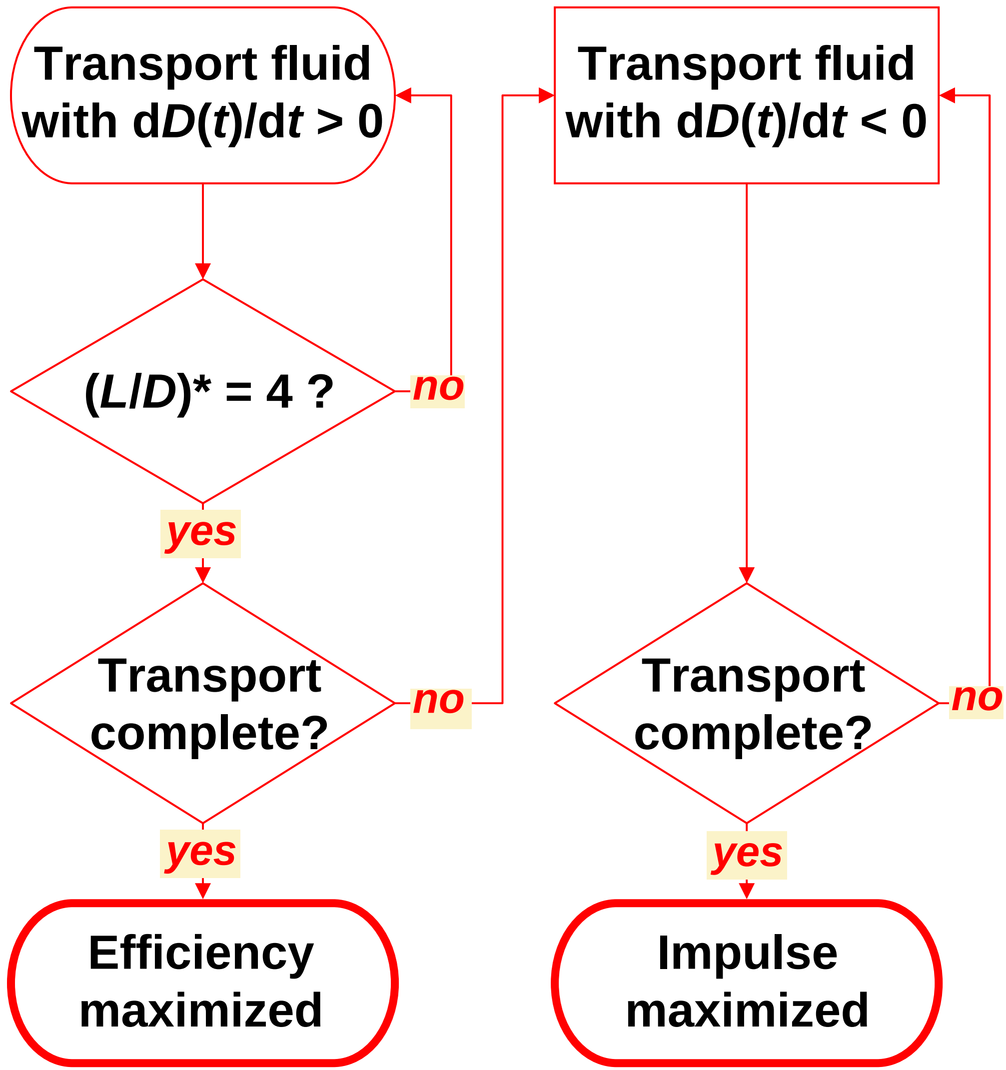

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Animal swimming revisited

- Squid rely on jet flow for high-speed swimming and escaping predation

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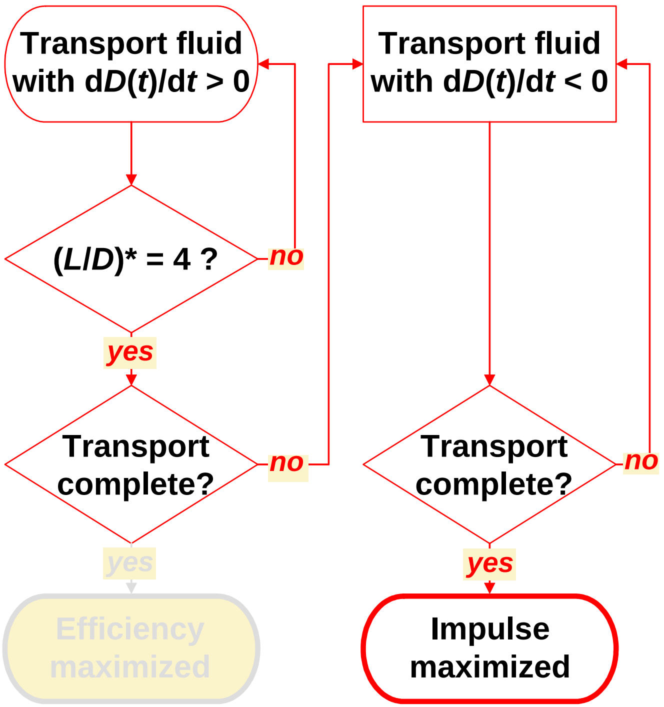

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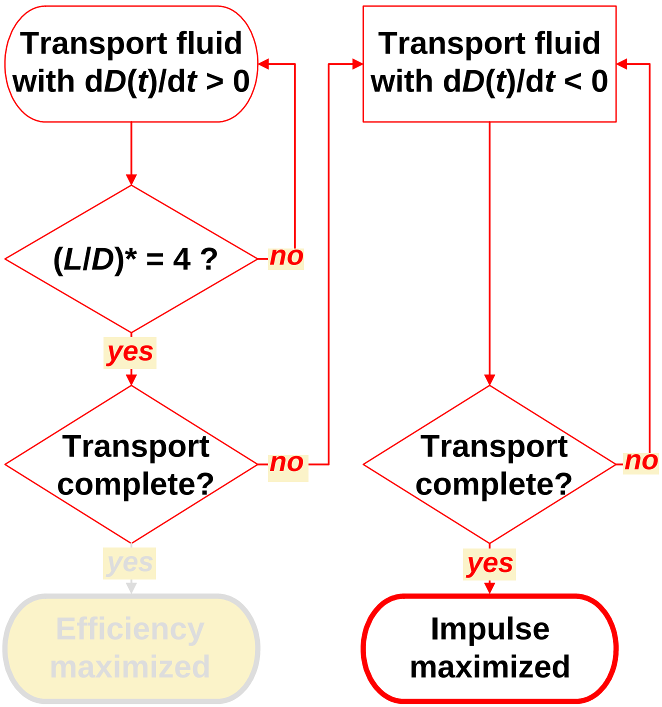

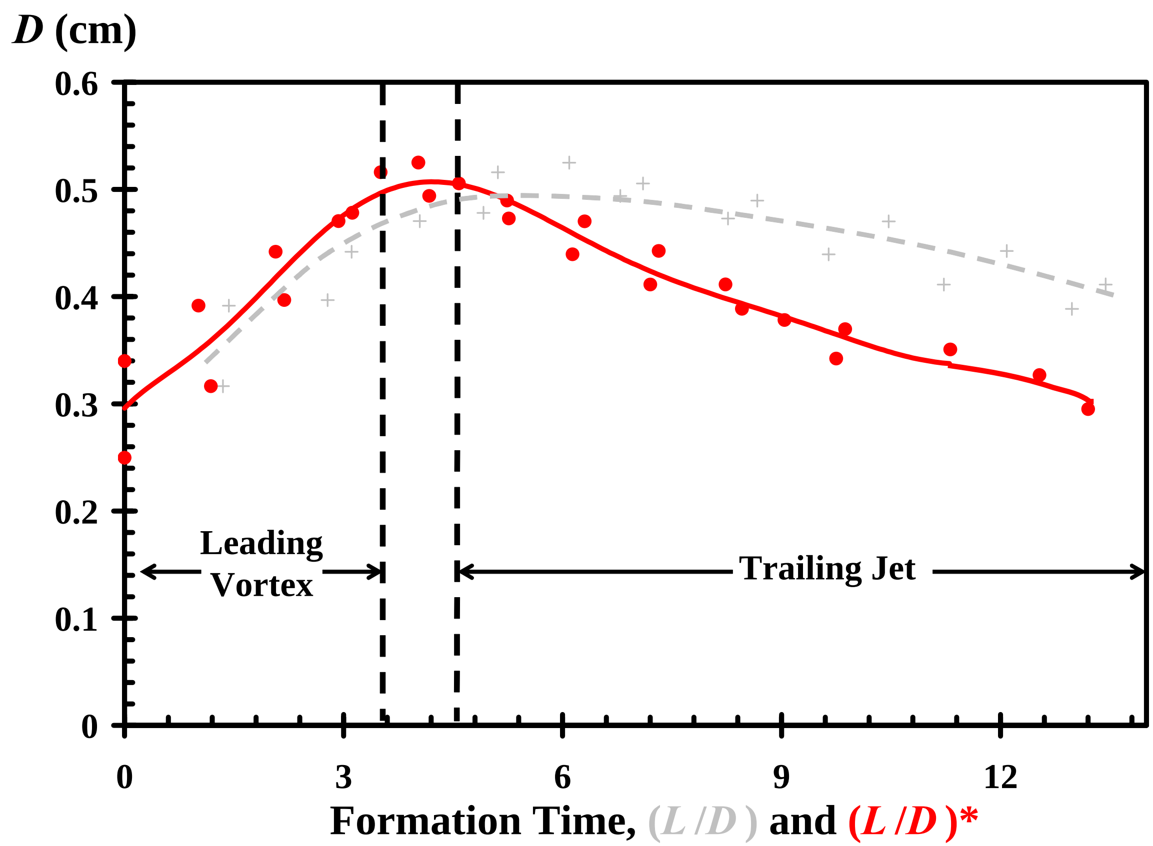

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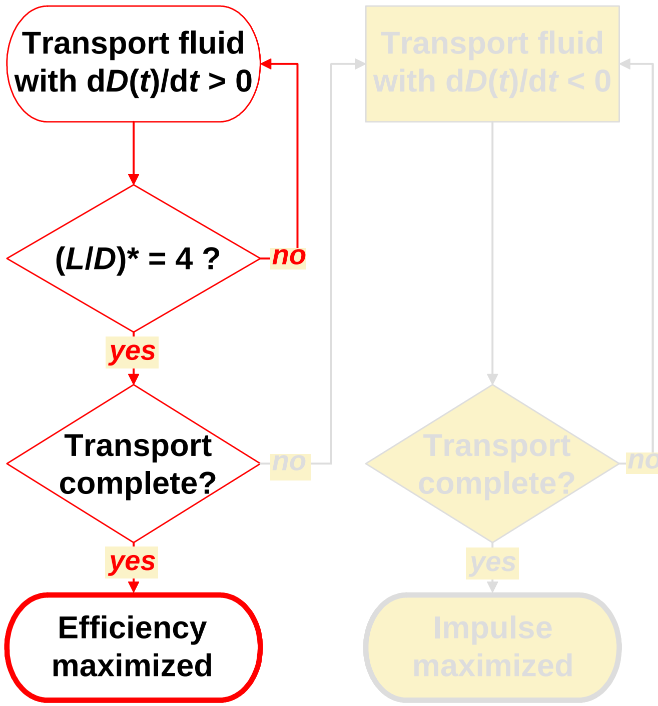

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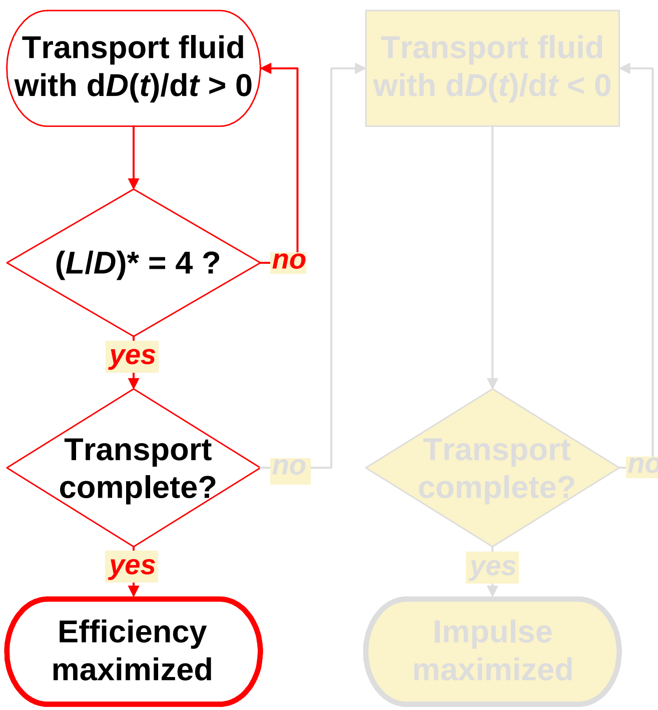

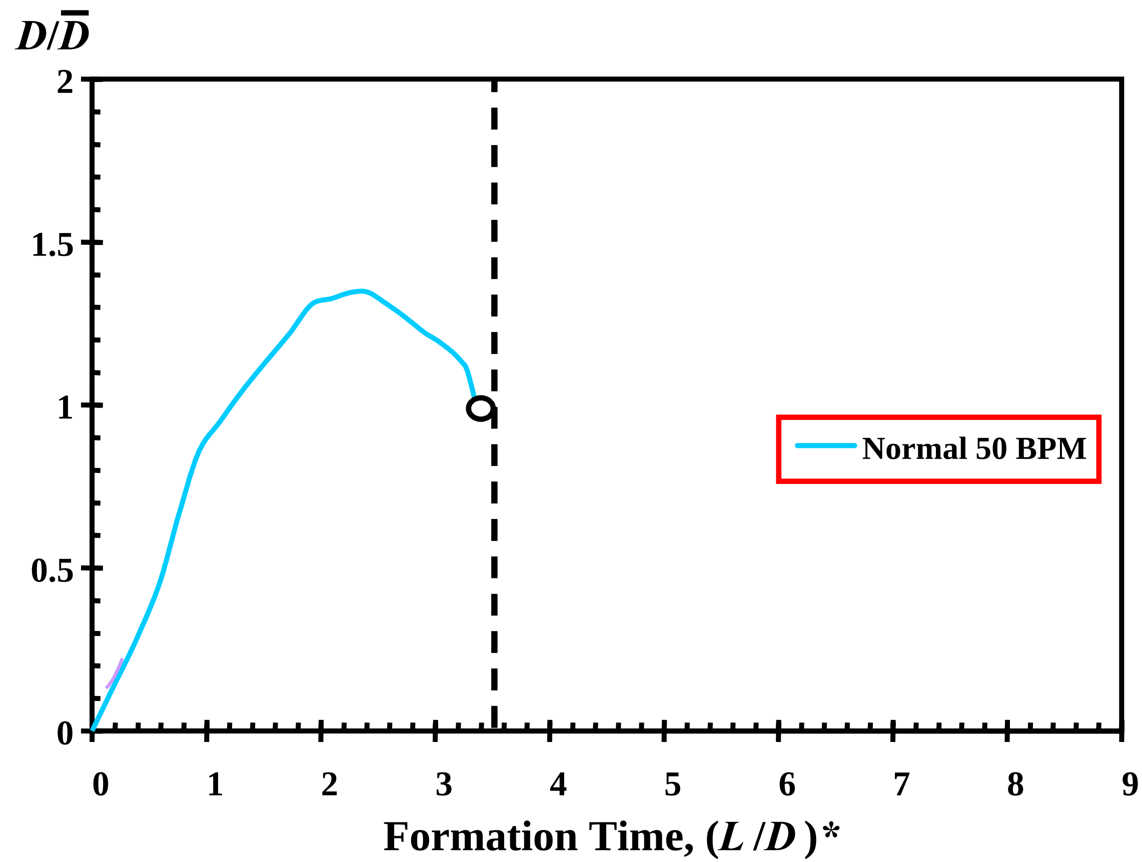

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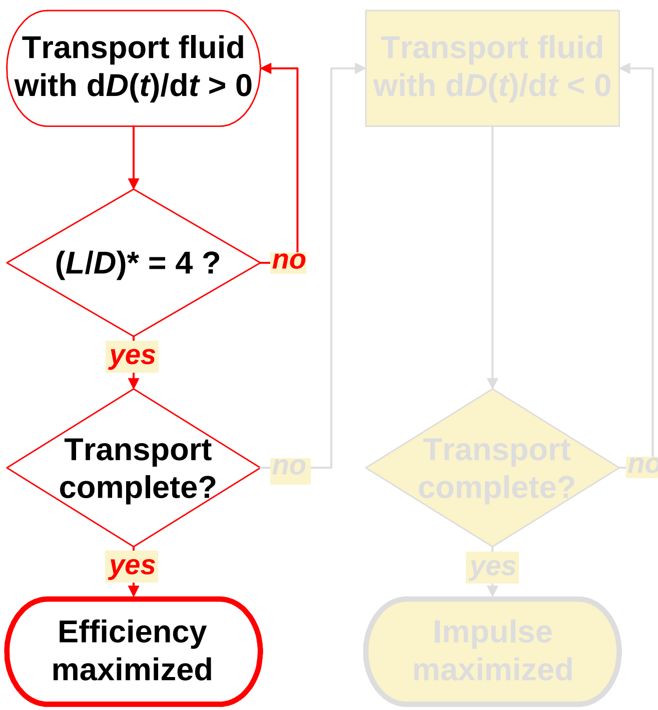

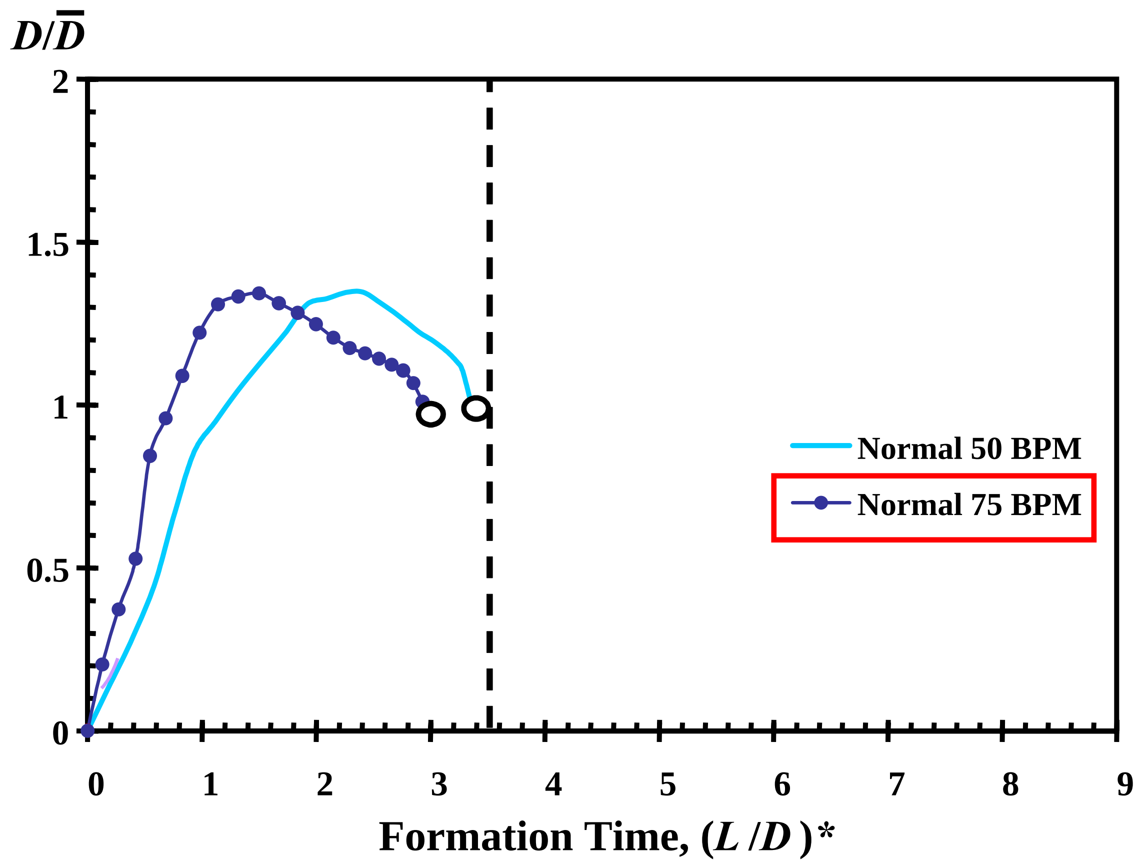

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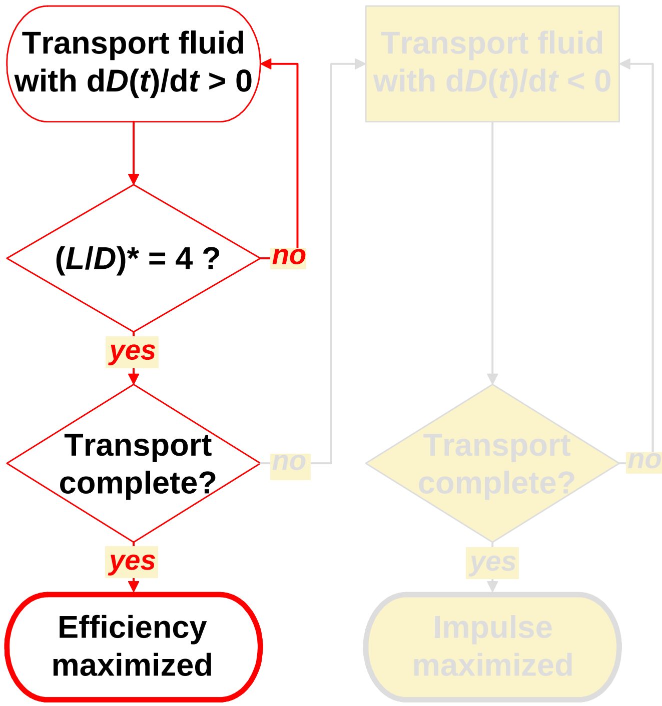

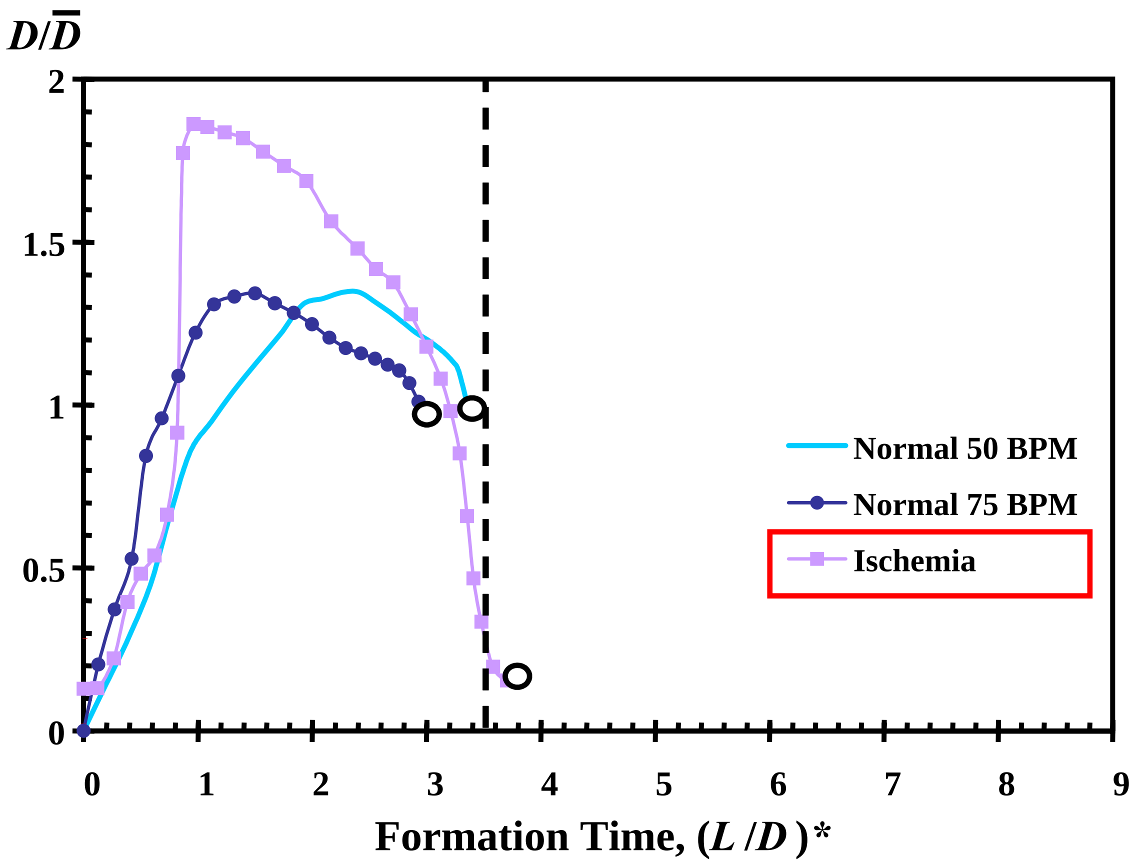

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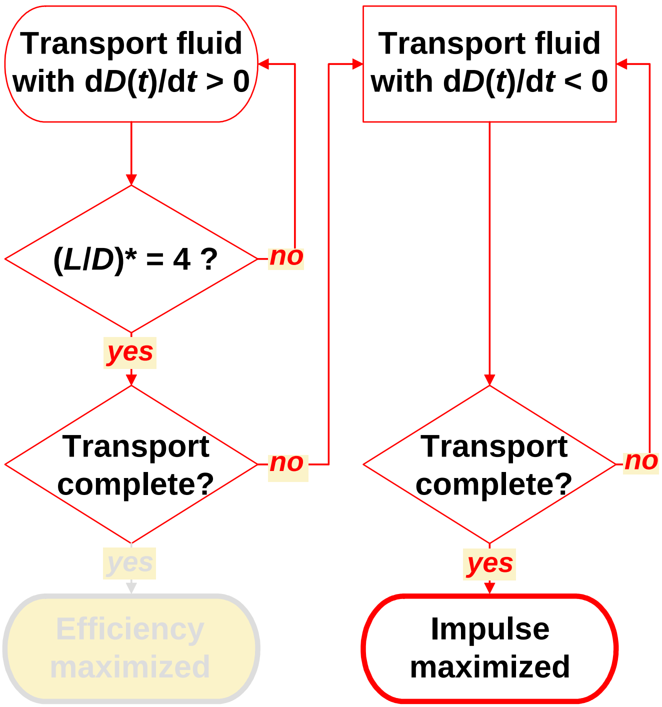

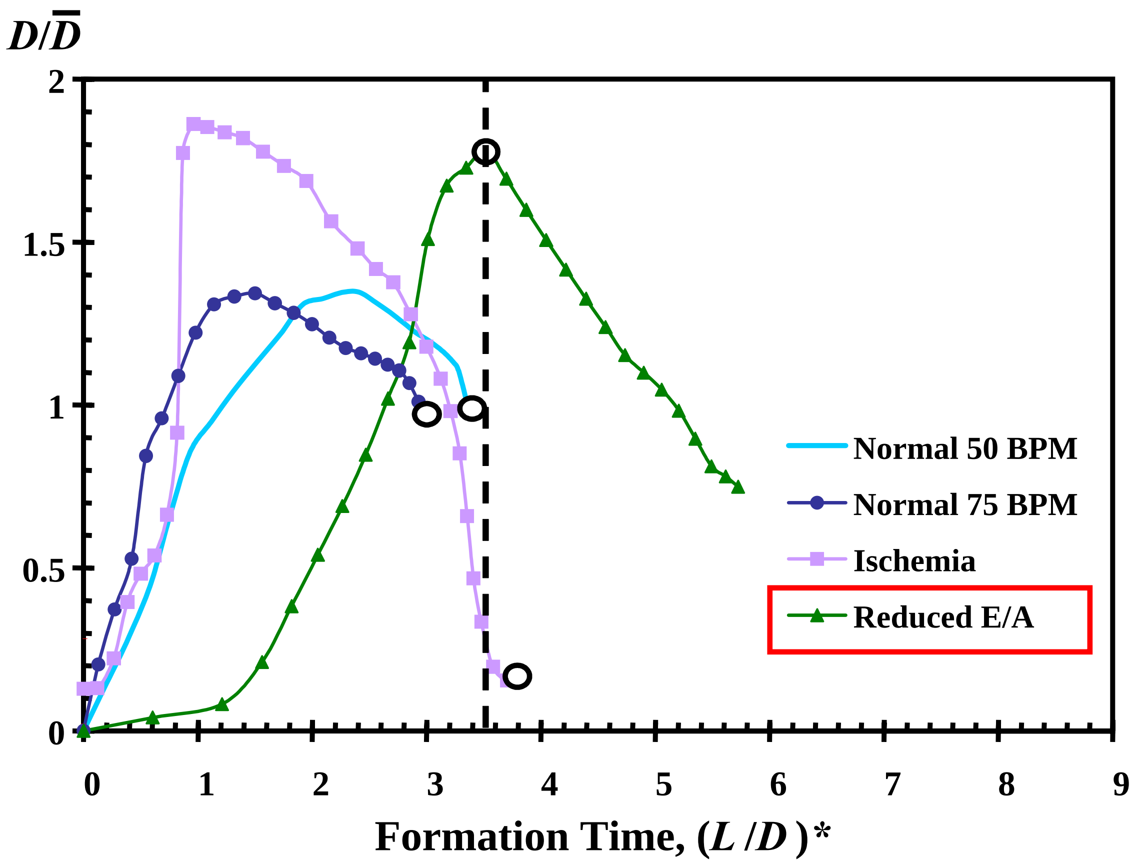

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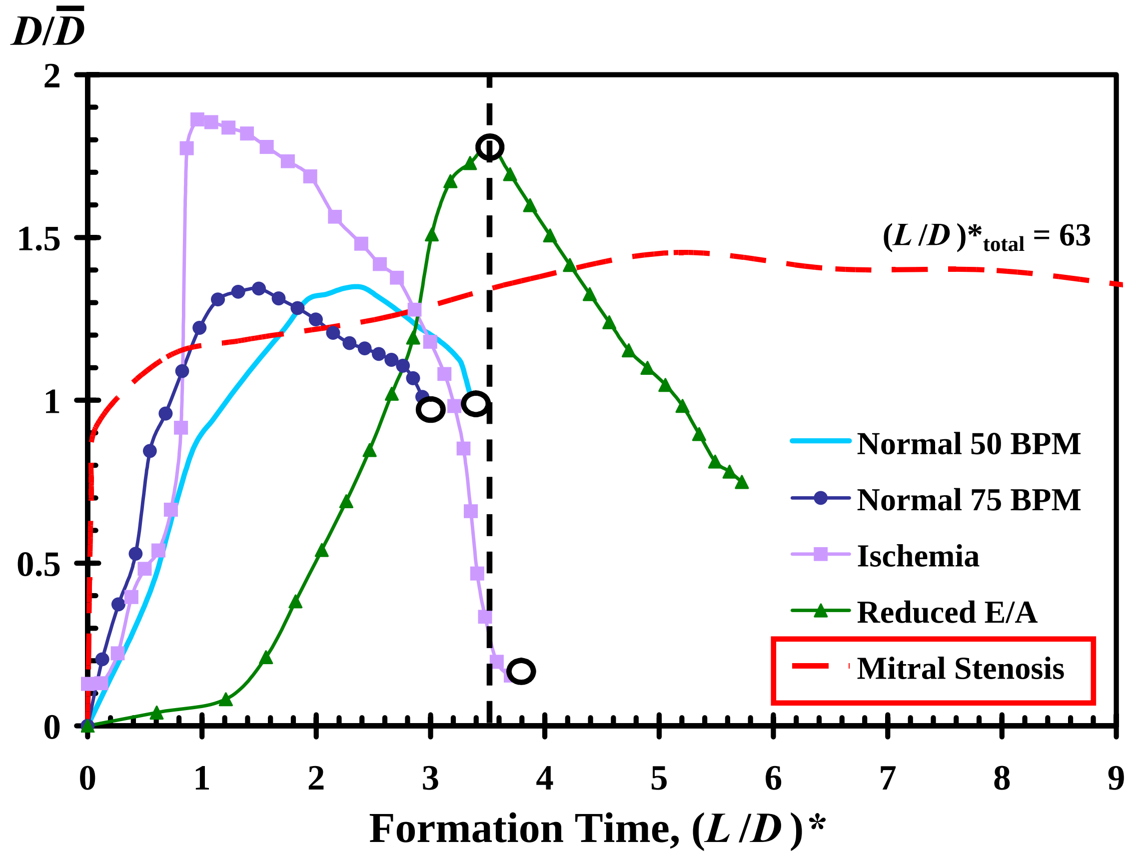

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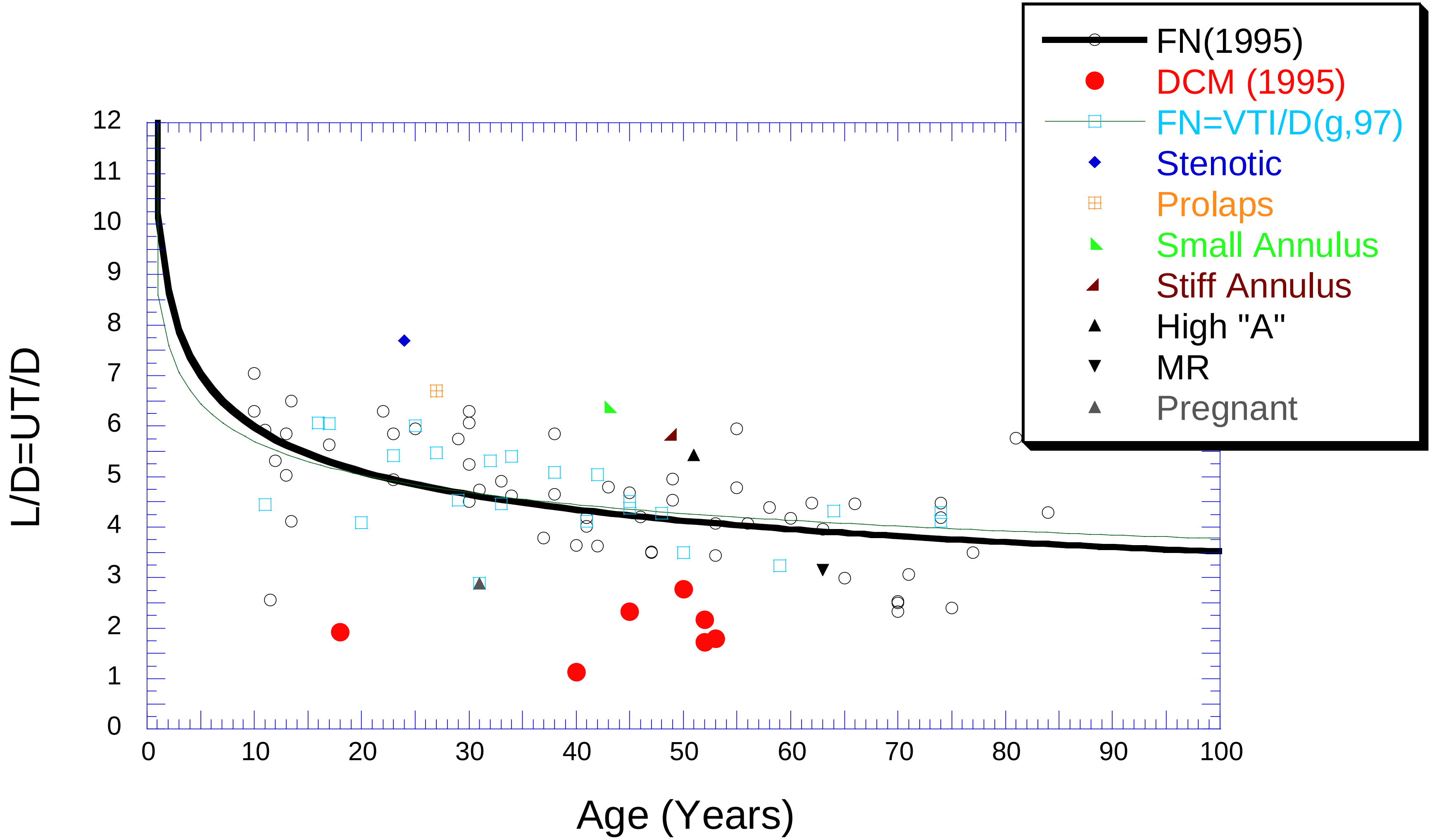

FN(1995)
DCM (1995)
FN=VTI/D(g,97)
Stenotic
Prolaps
Small Annulus
Stiff Annulus
High "A"
MR
Pregnant
L/D=UT/D
Age (Years)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
10
20
30
40
50
60
70
80
90
100

Conclusions

Do biological systems exploit vortex ring formation for optimal fluid transport?

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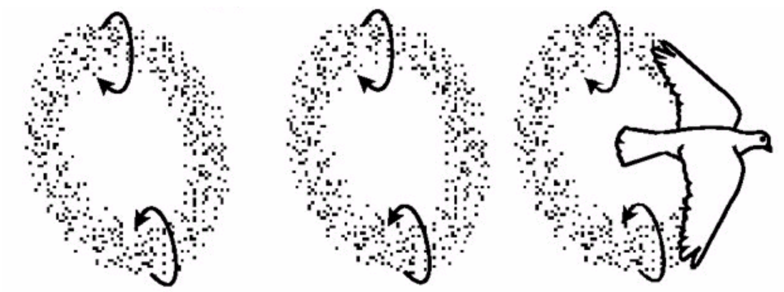
Do biological systems exploit

Yes, both mobile and

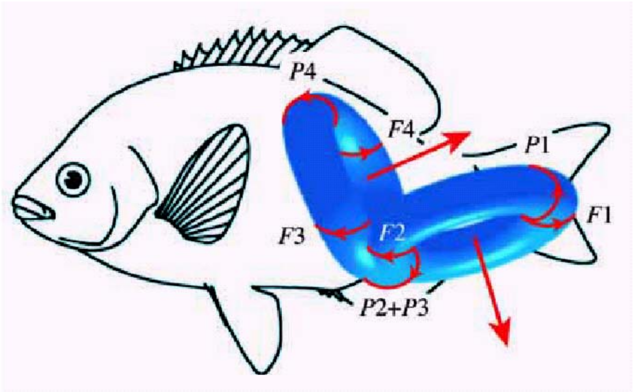
Comments

The vortex ring motif studied here is not limited to jet-based fluid transport…

Flapping

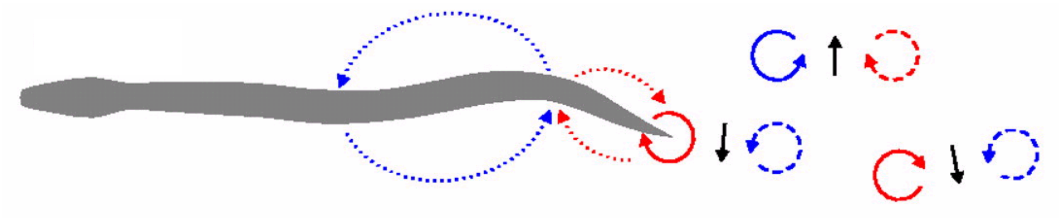


birds (Rayner, 1988)



fish (Drucker, 2000)

Undulating



eels (Tytell, 2004)

Paddling

frogs (Johansson, 2004)

Comments

…therefore, in order to better understand the physics and evolutionary incentives behind other vortex-based mechanisms, we need

To include realistic boundary and flow conditions such as compliance and co-flow

To investigate physics of individual events of vortex formation in the context of "Dynamic Formation Time" rather than Strouhal frequency

Acknowledgements

Special Thanks to

John O. Dabiri

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K. Mohseni (Colorado-Boulder), I. Bartol (Old Dominion), Michael Shusser (Technion), Moshe Rosenfeld (Tel Aviv), S. Colin (Roger Williams), J. Costello (Providence)

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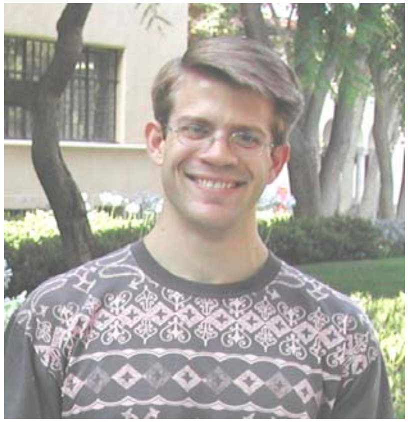
JOD



PSK