

Jellyfish: the Holonomist of the Sea

What a bell taught an instrument about memory, hovering, and the loop that encloses nothing

Matthew “Bear” Schulz · ORCID 0009-0000-0956-5743 · independent researcher · September 2026 · CC BY 4.0

Preprint. Not peer reviewed. A checkpoint on a road; the Declaration at the end says what this is and is not.

Abstract

A jellyfish swims with a stroke that, on paper, cannot work: rim and lip contract and relax as one motion run forward and back, a closed loop in the space of shapes that encloses no area, and in a fluid without memory such a loop carries a body nowhere. This paper builds an instrument for that stroke — an axisymmetric viscous solver with a moving bell, a leash, a valve and a wake reader — and reports what the loop does when the water remembers. Seven findings. The stroke lands on its own wake: the next cycle’s displacement falls by a third of a radius for every period of rest inserted before the stroke, on a straight line, at both grid resolutions. With a one-way apex cap that holds its breath, the same stroke goes almost nowhere — station-keeping within the instrument’s floor at both grid resolutions tested, with the sign of the residual drift not yet resolved. The energy the bell parks is in the stop vortex under its rim, not in the ring it launches, and at water viscosity on a slow stroke that vortex is shed rather than kept. The ring’s memory grows with Reynolds number while the body’s does not, held or free. The free bell runs at a power factor of -0.08 : ninety-nine percent of what it does to the water comes straight back. A valved bell on a long return becomes a through-flow duct, a jet the animal does not have. And the instrument has a floor, stated first: a rigid reciprocal squeeze at Reynolds number one moves a twelfth of a radius per cycle where the scallop theorem demands zero. Every figure regenerates from a named script and run file; every limit is on the page.

Preface — how this paper came to be written

Many months back I started a speculative engineering paper on jellyfish propulsion. It was a good idea and a fun one, and after a day of scoping it went on the shelf in May. The holonomy projects were calling and time was the one thing I could not make more of. So I spent the next hundred days loop-walking projects across domains — number theory, geodesy, protein knots, the sky — before I came back to it.

I knew going in what everyone knows about jellyfish: that they are, in the literature, among the cheapest swimmers alive for the distance they cover, that they are quiet, and that they are slow. My original intent was modest, to take engineering lessons from an animal that spends so little to go so far. What I had not expected was that a hundred days of loop walking would change what I saw when I looked at one. After thousands of hours, several manifolds and dozens of substrates, I returned to the quiet world of the bell with a loop walker’s eyes, and the animal had become a different object. Even without the vocabulary, you can watch a jellyfish and witness engineering details that only an evolutionary master-craftsman could have arrived at, and once you have the vocabulary you can name them: closed loops in the space of shapes, a wake that remembers, rings launched and rings parked and a parked ring used as a wall to push against.

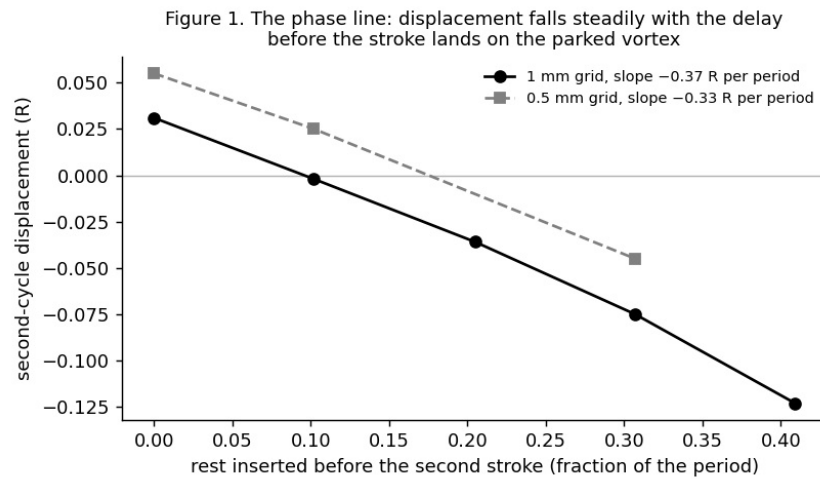
A jellyfish uses almost no motion to stay where it is. In marine engineering we would call that station-keeping; watching the animal, the word is hovering. The paper uses both, on purpose: station-keeping is the job, hovering is how the animal does it. By the halfway point of the project the jellyfish had a nickname, the Holonomist of the Sea, and by the end it had become the program’s poster creature. No spoilers, but it was a tougher and deeper project than Cascadia, and what it taught keeps generating papers and engineering lessons: the rings, the articulating rim, the scallop that cannot swim, the blobs and the blobs of blobs on the simulation grid, the leash, the stroke lengths and their timings, the stabilising ring, the parked ring, the ring used as a wall, and all the loops.

The jellyfish is a machine that, on a first calculation, should not work. Nature evolves winners because the losers do not survive, and this one evolved a great deal of holonomy inside a quiet bell, and with it a performance envelope that a machine which should not work has no business having. What follows is an attempt to measure how.

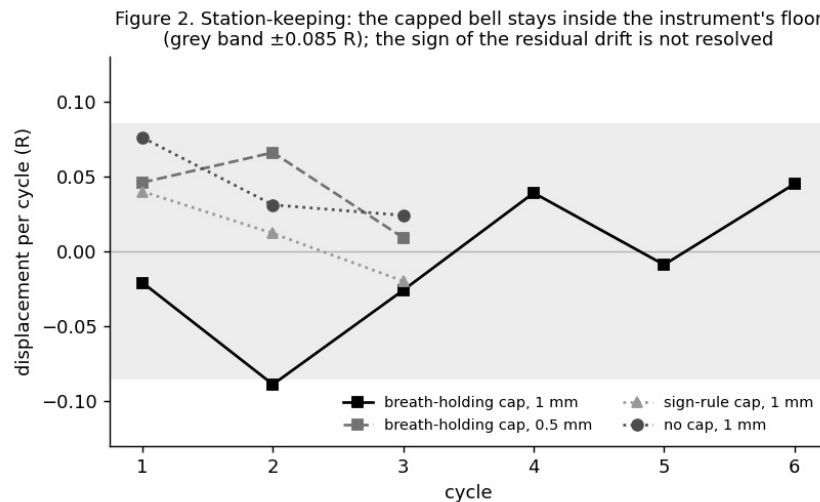
1. What we found

Seven things, each with its figure. The definitions, the instrument and the ladder of runs that produced them follow in sections 2 to 4; a reader who wants only the findings can stop at the end of this section.

The stroke must land on its own wake. The same 40/60 stroke run twice, with a rest inserted before the second stroke. On the one-millimetre grid: no rest gives $+0.031$ R in the second cycle; a tenth of a period of rest gives -0.002 ; a fifth -0.036 ; three tenths -0.075 ; four tenths -0.123 — five points on a straight line, about -0.37 R per period of rest. On the half-millimetre grid the line is still there with the same slope, -0.33 R per period, but shifted: $+0.055$, $+0.025$ and -0.045 at rests of zero, a tenth and three tenths. The first cycle is identical across the runs on each grid ($+0.076$ at 1 mm, $+0.040$ at 0.5 mm), as it must be. So the finding that survives resolution is the slope: the displacement per cycle falls steadily with the delay before the stroke lands on the vortex the last stroke parked, at a third of a radius per period, and the straightness reads as that vortex fading at a steady rate through the window the stroke can land in. The absolute values do not survive: the offset moves by three hundredths of a radius between grids, and the zero crossing moves from a tenth of a period to about a sixth. The displacement per cycle of this stroke is a reading of the wake’s phase, not a property of the stroke — and it is a reading the instrument resolves only to a few hundredths of a radius.

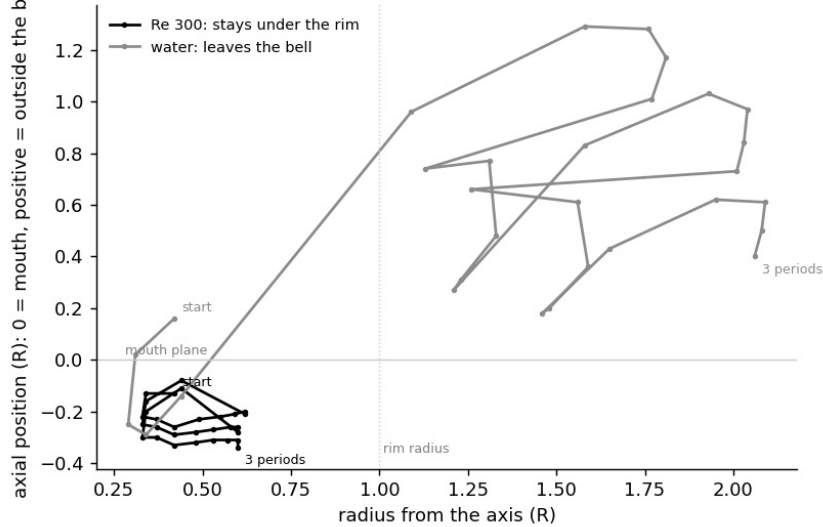


A bell that holds its breath keeps station — within the instrument's floor. Add a one-way cap at the apex that opens above five percent of the rim's peak speed and closes below minus five, and the free 40/60 bell runs six cycles on the one-millimetre grid at -0.021 , -0.089 , -0.026 , $+0.039$, -0.009 and $+0.045$ R: a mean of one hundredth of a radius, no runaway. On the half-millimetre grid the same bell runs three cycles at $+0.046$, $+0.066$ and $+0.009$: still small, still without runaway, but the other sign, a mean of four hundredths of a radius mouth-first. What survives resolution is that the valved bell moves an order of magnitude less per cycle than the swimmer (-0.19 to -0.78 R for the fast push) and stays inside the instrument's own floor of ± 0.085 R; what does not survive is the sign, or any claim about which way it drifts. The honest sentence is that the breath-holding cap turns the 40/60 swimmer into a station-keeper to within the resolution of this instrument, and that the instrument cannot yet say whether it is a true hover or a slow drift of either sign. The animal hovers; the marine engineer calls it station-keeping; the instrument says: the same stroke, valved, goes almost nowhere.



The energy is parked in the stop vortex, not the launched ring. The ring that leaves the mouth is a thin ring only through the first three tenths of the first cycle; once the lip folds its core outgrows its radius and it is a spreading sheet. The vortex that stays a ring is the one parked under the rim at the end of the return. It loosens in each contraction and tightens in each return, and the energy in its core grows cycle over cycle. On a slow stroke it stays under the rim at Reynolds numbers 30, 100 and 300 — and at water viscosity it does not: at 0.6 T of the first cycle it leaves the bell, travels two radii out, and stays out. The recapture object is parked at Re 300 and shed in water, on this stroke.

Figure 6. The stop vortex on the slow stroke: parked at Re 300, shed at water viscosity



The two clocks are not one. The water's memory of the parked ring grows with Reynolds number, from about 4 s at Re 30 to 7 at Re 100 to at least 15 at Re 300 and beyond the window in water; the body's memory of the push does not: held on a leash the force forgets in about half a second at every viscosity, and free the bell comes to rest about 2.7 s after the contraction at every viscosity. Whatever the ratio of the two clocks is, it is not a constant of the comma curve.

Figure 5a. The two clocks: the ring's grows, the body's does not

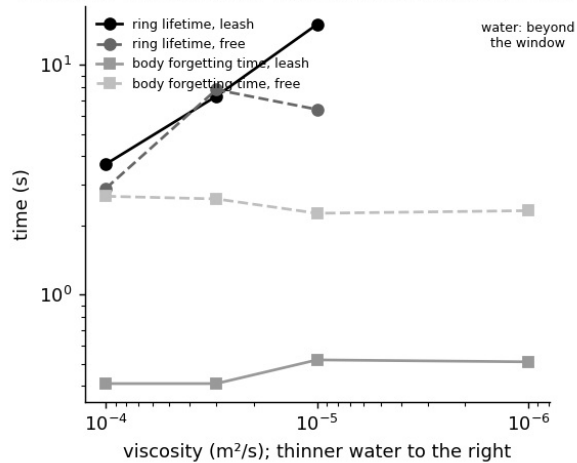
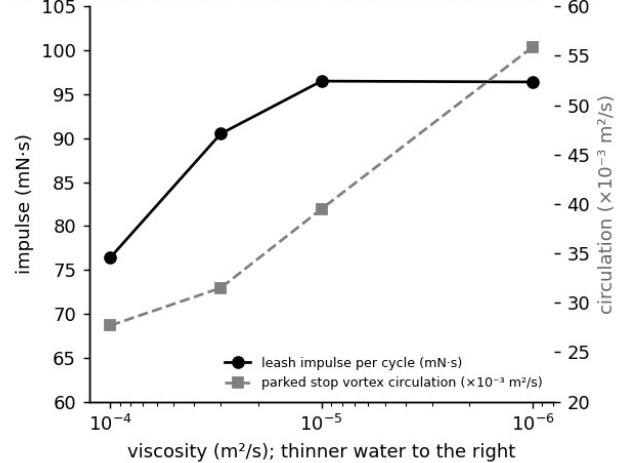
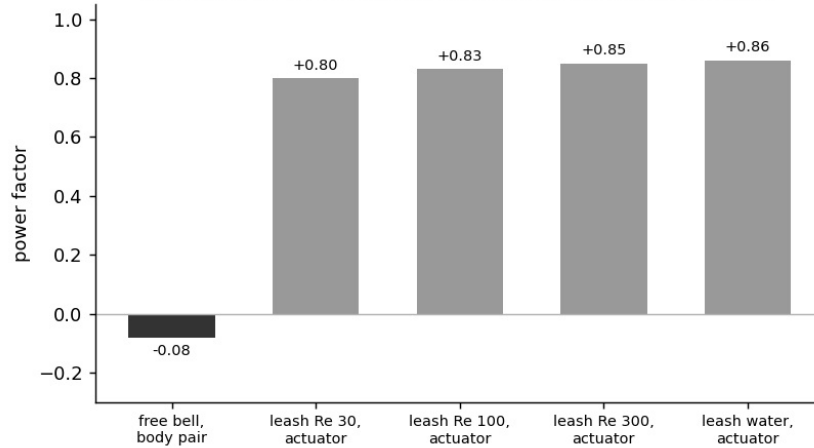


Figure 5b. What the bell feels versus what the water keeps

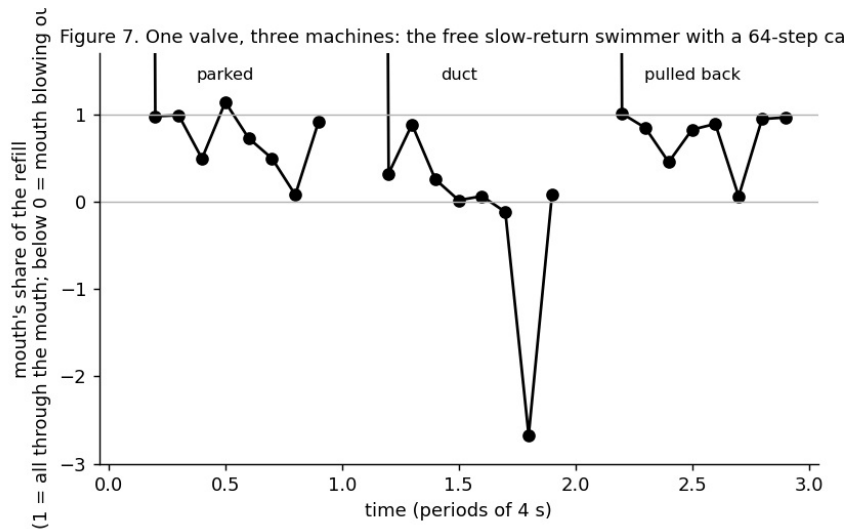


The free bell is a spring. Its power factor, the real power it exports over the apparent power it exchanges with the water, is -0.083 at one millimetre and -0.04 to -0.06 at half a millimetre; the reactive fraction is above 0.996 on both grids, and the finer grid makes the spring purer, not weaker. Ninety-nine percent of what the bell does to the water comes straight back, and the stroke's whole job is the residue. Held on a leash the same actuator's effort is four fifths real.

Figure 8. Power factor: the free bell is a spring; the held bell is a load

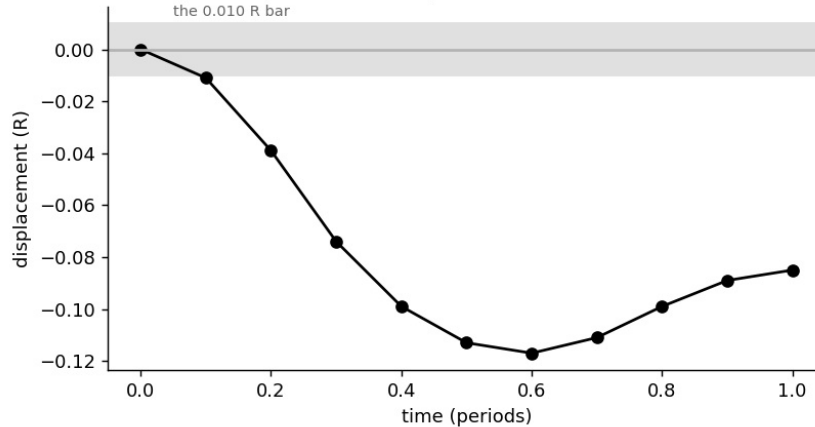


One valve, three machines. On a four-second return the breath-holding valve does not hover; it switches between three modes according to the body's speed at the start of the return. Parked: the refill enters through the apex, the mouth's suction that would drag the bell forward is gone, and the body sits. Duct: the mouth blows out while the cavity fills through the apex, water passing straight through the bell, a start ring shed on the way, the body accelerating through the whole return. Pulled back: the cap shuts, the refill comes through the mouth against the wake, and the bell backs up. The mechanism of the duct is known, and it is measured at the cap itself: the faster the body moves apex-first, the higher the dynamic pressure at the apex, the wider the cap stays open — the cap's open fraction climbs from 8 to 20 percent through the duct's return while 2 to 96 cubic centimetres a second enter at the apex — and the wider it is open, the more through-flow, the more thrust, the faster the body. That is a feedback loop with the right sign to run away; a cap that opens slowly (a 64-step ramp) lets the loop saturate at about a quarter of a radius per second, and a cap that opens fast (4 or 16 steps) lets it diverge. What is redeeming about it is twofold. It is the only stroke in this paper that makes a start ring during the return, so it is a through-flow propulsor — a valved bell acting as a ram duct — which the animal cannot be because a bell has no apex hole; and it is the clearest instance in the programme of a plant whose gain depends on its own output driven by a relay with a rate limit, which is a control problem with known remedies (a rate-limited cap is the crude one; a cap scheduled on body speed is the obvious next). It is fenced as not a design because the knife edge between 16 and 64 steps is untested between those values and the free-body sign is below resolution; it is kept because a through-flow bell is a machine worth pointing a specialist at.



The instrument has a floor, and it is stated first. A rigid reciprocal squeeze — the pump's radial breathing, a line in the space of shapes — with a massless body at a Reynolds number near one moves $-0.085 R$ per cycle. The scallop theorem says zero. That twelfth of a radius is the smallest displacement this instrument can be trusted to distinguish from nothing, and no number below it in this paper is read as swimming.

Figure 9. The instrument's floor: a reciprocal squeeze at $Re \approx 1$ drifts to $-0.085 R$ where the scallop theorem demands zero



2. What a reader needs first

This section carries no result. It gives the four pictures the rest of the paper leans on; every formula in it is said in words, and prior art is named at abstract level.

The space of shapes, and a loop in it

Forget for a moment where the jellyfish is and ask only what shape it is. At any instant the bell has a rim radius and a lip angle, and those two numbers are a point on a map. As the animal swims the point moves: the rim closes, the lip folds, the rim opens, the lip unfolds, and the point comes back to where it started. One stroke is one closed loop on that map, and the map is called the space of shapes. Everything in this paper happens on it.

There are two kinds of loop. If the rim and the lip move together — closing as one and opening as one, the same path run forward and then backward — the point traces a line out and traces the same line home. The loop encloses no area. If the lip lags the rim, folding a moment after the rim closes and unfolding a moment after it opens, the point goes out along one path and comes home along another, and the loop encloses an area between them. The first kind is called reciprocal; the second is not. The scallop is the textbook reciprocal swimmer: one hinge, one angle, out and back along the same line.

Why area is the whole story when the water forgets

Now put the shape back in water and ask how far the body moves in one loop. The answer depends on whether the water remembers.

Water forgets when it is thick, or the body is small, or the motion is slow — when what an engineer calls the Reynolds number is small. A tiny swimmer in honey lives in a fluid that forgets instantly: the moment the body stops moving, the water stops too, and nothing of the last stroke is left over. In such a fluid the displacement per loop depends on the loop's shape and on nothing else — not on how fast it was run, not on what came before. Run the loop slowly or quickly, the body arrives at the same place. And a loop that encloses no area gives no displacement at all: the body goes out on the forward half and comes back exactly on the mirror half. That is the scallop theorem (Purcell, 1977): in a fluid with no memory, a reciprocal swimmer cannot swim. The rule that connects the displacement to the loop is a holonomy — the same word the rest of this program uses for a quantity that depends on the closed path taken and not on the speed along it (Shapere and Wilczek, 1989, carry the swimming case in full) — and for a memoryless fluid the holonomy is set by the enclosed area. Geometry is the only lever.

What memory adds, and what it costs the theorem

Water remembers when it is thin, or the body is large, or the motion is fast. A jellyfish the size of a hand at one stroke a second is far into this regime. When its rim closes it launches a ring of spinning water out of the mouth, and when the rim opens it leaves a second ring, spinning the other way, parked under its own edge; both rings outlive the stroke that made them by seconds. The next stroke is not performed in still water. It is performed against what the last stroke left behind, and the displacement per loop now depends on the loop's shape *and* on the state of the wake at the moment the stroke begins.

This is where the scallop theorem stops being a prohibition and becomes a baseline. A reciprocal loop can now carry a body, because the wake supplies the asymmetry the shape lacks: the parked ring is a wall the next contraction pushes against. It also means a memory-driven swimmer's displacement is not one number but two: the part its geometry earns, which is what a memoryless fluid would give it, and the part its memory earns, which is everything else. The bumblebee is the familiar case of the same mistake in air. A steady-flow calculation with fixed wings and no wake once said it could not fly; it flies on the vortices its wings shed. The jellyfish, like the bumblebee, cannot work on any page that leaves the wake out.

How the paper separates the two parts: the mirror test and the floor

Two devices make the split measurable rather than rhetorical. The first is the mirror test. Run the animal's stroke, then run the same stroke with the fast half and the slow half exchanged — the contraction drawn out and the return made quick. In a fluid with no memory the two runs give the same displacement, because the loop's shape has not changed; only its timing has. In a fluid with memory they differ, and the difference is the memory's share, read directly. A stroke whose mirror gives a very different answer is living on its wake.

The second is the floor. Before believing any small displacement, the instrument is made to run the one case whose answer is known exactly: a rigid reciprocal squeeze in a fluid thick enough to forget, where the theorem says the body must go nowhere. The numerical bell moves by a twelfth of a radius per cycle in that test. That number is not a discovery about jellyfish; it is a fact about the instrument, the smallest displacement it can be trusted to distinguish from zero, and it is stated first so that everything below it in the pages that follow is read as noise, and everything above it as water.

The one sentence to carry forward

Shape decides what a swimmer can do in a fluid that forgets; memory decides what it does in a fluid that does not; and the animal in this paper has chosen a shape that earns nothing on its own, so that everything it does is memory — which is why a tenth of a period of rest before a stroke can turn its swim into a hover.

3. The animal and the instrument

The bell. A hemispherical shell of radius $R = 5$ cm, height $0.8 R$, with a rim that contracts by 45 percent of R over the contraction and relaxes over the

return, and a lip 0.3 R long that folds up to 45 degrees as the rim closes. The stroke is a raised cosine in time: a contraction of length TC, a return of length $T - TC$, the fraction TC/T called the duty. The animal's stroke, read from the author's own frames of a sea nettle, is duty 0.4 on a one-second period — a 0.4 s contraction and a 0.6 s return — and is called the 40/60 stroke throughout. A 0.1 duty on a four-second period is the slow return; a 0.15 s contraction is the fast push.

Free, tethered, on a leash. A free bell is one whose body moves under the fluid force on it, with a mass twice the displaced water, and its displacement per cycle is read in radii, negative meaning apex-first, the animal's way. A tethered bell is held at zero speed by a leash, and what is read instead is the impulse per cycle the leash carries, in millinewton-seconds, negative meaning the bell pulls apex-ward. The leash is the paper's force balance: it separates what the water does to the body from what the body then does with it, and every tethered number is a force the free bell would have felt.

The wake reader. Vorticity in the water is summed by sign into a launched (plus) circulation and a parked (minus) circulation, each with a centroid, a core radius, an energy in the thin-ring approximation and a tracked circulation in a window that follows the ring. The event probe at the rim reports when the flow there reverses; the coast is the last time before the next stroke at which the body (free) or the leash force (tethered) falls below five percent of its cycle peak and stays there — the forgetting time.

The mirror stroke. The same shape loop run with the fast and slow halves exchanged. In a fluid with no memory it gives the same displacement; the difference is the memory's share.

The valve. An optional hole at the apex of radius 0.3 R, with a cap that either opens on the sign of the local inflow (the sign rule) or opens above a threshold speed and closes below its negative, over a ramp of several time steps (the breath-holding, or hysteresis, cap).

Jitter. A rest inserted before a stroke, so the stroke lands at a chosen delay on the previous stroke's wake.

Resolution and fidelity. Runs are at a grid spacing of 1 mm unless stated, with 0.5 mm checks; 4 mm runs are trends whose signs are not read; 2 mm runs are read as sizes. The leash impulses converge at 0.5 mm to within a few percent; the free bell's displacement per cycle on the 40/60 stroke does not — it moves by a few hundredths of a radius between 1 and 0.5 mm — so free-body displacements smaller than about 0.05 R per cycle are reported with that uncertainty and their signs are not read. Every tool version reproduces the previous version's physics digit for digit on three reference runs, and the fidelity check is run before every batch.

4. The ladder of runs

The instrument was built in stages, each adding one physical ingredient and pricing it against the last. The table is the whole ladder; the text below it carries only what changed the story. The full account of each stage is Appendix B.

stage	what was added	the question	what it gave	verdict
the pump	a rigid rim breathing radially, no lip	can a reciprocal loop move at Re 300?	+0.06 R per cycle, mouth-first	the baseline, and the wrong direction
shape	the bell flattens and rounds with the rim	does shape change alone swim?	small, mouth-first	no
lip	the lip folds and shuts the slot at end of contraction	does the lip make the animal's direction?	-0.11 R per cycle, apex-first, all three parts on	yes: the lip is the swimmer
plug	the oral arms as a central plug	does the plug help?	within the floor	no effect read
the leash	the bell held at zero speed	how much does the water push?	-86 mN·s per cycle at 40/60	the force balance
the return axis	return 1.0 → 5.0 s at a fixed 0.4 s contraction	is a long return worth it?	impulse per cycle flat, 91-99 mN·s; mean force falls with $1/T$	the water rests; the stroke does not gain
the push axis	contraction 0.8 → 0.15 s at a 3.6 s return	is a faster push a stronger ring?	-0.01 → -0.78 R per cycle	yes, steeply; the 0.1 s rung is dropped by rule
the mirror	fast and slow halves exchanged	what is the memory's share?	the two runs differ; the difference is the memory term	the comma curve
the valve	a one-way apex cap	can refill come from the apex?	hover on the 1 s stroke; runaway on the 4 s stroke	the hoverer; the duct
jitter	a rest before the stroke	does the phase matter?	five points on a line	the memory reading, confirmed
viscosity rungs	Re 30, 100, 300, water	do the clocks scale together?	ring memory grows; body memory does not	the two clocks

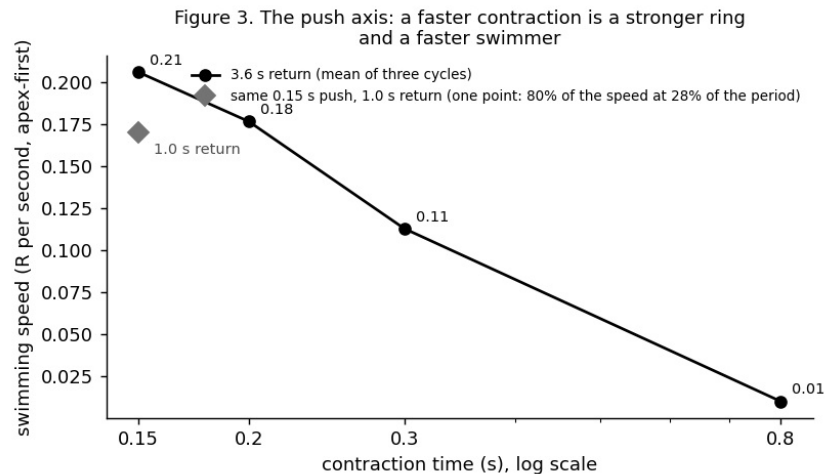
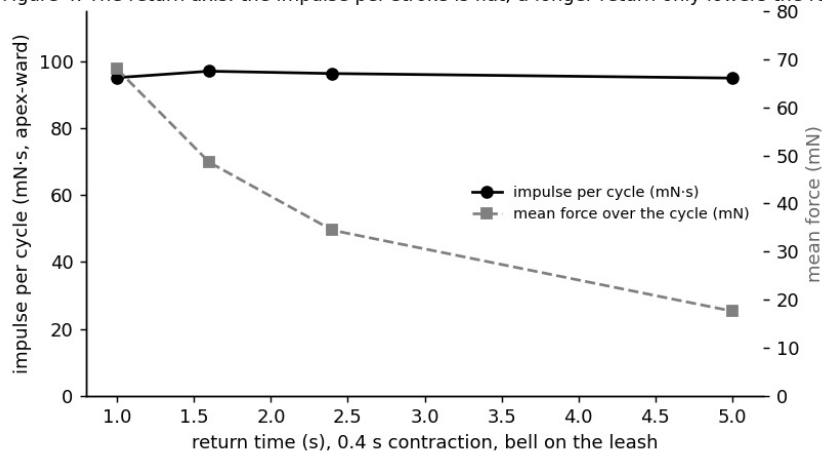


Figure 4. The return axis: the impulse per stroke is flat; a longer return only lowers the rate



The push axis and the return axis say complementary things. A faster contraction makes a stronger start ring and a faster swimmer, steeply: from a 0.8 s push at -0.01 R per cycle to a 0.15 s push at -0.78 . A longer return does not: on the leash the impulse per stroke is the same within ten percent from a one-second return to a five-second one, so what a long return buys is rest, and what it costs is rate. The animal's 40/60 stroke sits where the rest is just long enough for the parked vortex to be there when the next stroke lands, which is what section 1's first finding measures. Free, the slow-return swimmer gets faster as the water thins — a twentieth of a radius per cycle at Re 30, a third in water — while its own rest after the contraction stays at about 2.7 s at every viscosity.

5. What it means for a machine

Three machines fall out of the ladder, and they are not the same design. The pump is a rigid cap that breathes; it makes a jet, moves the wrong way for a swimmer, and is the baseline. The swimmer is the margin — the lip that shuts the slot — with the recapture of the parked vortex on the return; a machine that only pushes gets the contraction half of the budget and none of the recapture. The hoverer is the swimmer with the breath-holding cap, timed so that each stroke lands on the parked vortex at the phase that cancels the last; it keeps station with the water doing the work. Its falsification point is one line: a machine that cannot choose the phase of its stroke against its own wake cannot hover, because a tenth of a period decides the sign. The duct — a valved bell on a long return passing water straight through itself — is a fourth machine the ladder found and then measured: with a cap that opens over 4 or 16 steps the free body runs away; with 64 steps it settles at about a quarter of a radius per second, and the cap lines show the through-flow directly. It is kept as a mechanism and fenced as not yet a design, because the edge between 16 and 64 steps is untested between those values.

The tethered finding of rung 3 says what it says and no more: the starting ring is drawn back into the mouth during relaxation because the body is not moving through the water — refill inflow at the mouth near 20 mm/s against a ring self-speed near 7. A body swimming, or tugging, faster than its rings drift outruns the refill; a station-keeper in a current is carried clear by the current. The one bad case is holding position in still water, the habitat-tender's life, and the author has set it as the case the whole envelope must close: station-keeping on a leash with no appreciable movement, and how to engineer around it, including shifting the stroke through phase into a travelling rim mode. Four levers, cheapest first: break the coincidence that the mouth is both exhaust and intake, which the animal cannot and a machine can; slow the relaxation; launch the ring farther out; or row instead of jet, rim strokes with no cavity refill. The parked stopping vortex sits at about 0.75 R just inside the margin and is kept at water viscosity (rung 3, and rung 2 at 0.5 mm), so any intake path must leave that annulus alone.

The design options raised against that frame are priced one line each, in the design ledger's order. Intake screens laminarise at the 5 cm scale (wire Reynolds 20) and make turbulence at 5 m, and are prior art (the wind-tunnel screen) with a porosity that is already a solver knob. A piston with a planted stator is Gharib's piston-cylinder with the formation number near four as its cam profile, and its stator is planted by the intake stroke, not by a half push. A seep-refill dome is a pressure question and the pressure is small — half a pascal at 5 cm, seven at 5 m — so it is feasible and slow, which for station-keeping is the point, and the inflow arrives at the apex, off the protection annulus. A dome valve is the same one-line mask test as the seep dome. A paddle cylinder is a ctenophore, the largest ciliary swimmers, quiet and slow and very good at it, and the only option whose thrust does not depend on a ring surviving anything; it cannot run on the axisymmetric grid and is held for a tool. Facing foils that clap and open leave the reverse Kármán street every flapping swimmer leaves, prior art deep and positive, with no refill to protect and its originality located in the pairing. A tuned drumhead skin has structural resonance in the stroke band (Hoover's resonant bell made explicit) and no acoustic one, and its fundamental is a Bessel bell that is the best-shaped plunger. The ring as a calibration ping reads range, local viscosity, current and the stroke's own health from a known ring's return, at the cost of one stroke and with nothing acoustic for a listener to hear. The encoding frame: a ring is already encoded energy and its encoding is impulse, $\times 8$ leverage from entrained water, capped by the formation number; swirl is a loss for power and a channel for data, priced at rung 4. A body cannot gain from catching a ring it made; rupture is a gain channel only for rings another body launched — wireless towing, a swarm handing rings down a line — or rings the environment makes. Smoke rings passing inside one another are Helmholtz's leapfrog, and the lesson is that shooting a ring far does not help propulsion: the push is delivered at launch and afterward the ring matters only through the flow it induces back on the body; a far ring induces nothing, the parked one everything, and the animal already keeps the useful half at home. The scale law is the ten-second breath: the muscle-sheet cap becomes a power law for machines, and a 5 m cyber-jelly breathes every 13 s, moves 9 t of water per breath, on about 2.5 W.

For the leash the ranking from what the tools price now is refill geometry first, because it is a mask and a mass-balance line on the existing tool; the gearbox of \$5 second, because a standing $m \geq 1$ mode is a quiet idle with no volume flux and no refill at all, and a travelling mode is torque, volume-neutral, but pricing either needs the three-dimensional filament code; and slow breathing last, because the two-millimetre proof says a factor of two and not a sign. Every station-keeping number carries the half-millimetre resolution tag, since the protection annulus and the boundary layer that keeps or kills the parked vortex are millimetre physics on a five-centimetre bell. Cruise swims already; sprint stays an escape mode (§11).

One row added the breath-holding valve — a one-way apex cap with hysteresis (opens above +5% of the rim's peak speed, closes below -5%, four-step ramp). Its number is the six-cycle hover of the free 40/60 bell, mean -0.010 R per cycle with no abort; its fence is the slow-return abort at 1.044 T, priced before it is closed. On the leash it adds nine percent to the mean pull and steadies the push half only.

6. Limits and walls

The fast bell above 2 m/s was closed twice, by the formation number and by ω^4 radiation. Route B removes the monopole, and the velum run as an iris raises the formation number cubically by shrinking the nozzle ($FN = A \cdot L^2/D \cdot \omega^3$). Together they reopen a fast **sprint**: a squid escape jet, jet speed far above vehicle speed, Froude poor, quiet in the monopole sense — an escape mode, never a cruise. The slug's mass reopens only as a small tuning mass for frequency stability against changing added mass. The gas pocket as float below 30 m stays closed; the rigid float is the design. Matching two independent high-Q bells reopens only by coupling both volumes to one drive, which is Route B by another name. Deep rotors reopen in currents, already the salvage. The ionosphere never reopens; vacuum reopens as the other paper. The shedding shortcut reopens with a vorticity budget. The membrane-law constant and the "48% Froude" were errors, not limits, and stay dead. One limit of the instrument rather than the animal: the Stokes floor. A rigid reciprocal squeeze with the massless body at a Reynolds number near one moves 0.085 R per cycle where the scallop theorem says zero, against a pre-registered bar of 0.010 R. The

suspects are the re-rasterised body mask sweeping fluid and the five-step force average lagging a massless response; until one of them is removed every zero-memory number stays held, and no displacement under the floor is read as swimming. It reopens only when the known-answer test passes. One more fence of the instrument, a backward pass over the run files: the mass-balance column at the end-of-contraction row reads 3.5 to 4.0 in every run with or without a valve, and flips sign at water viscosity on the slow stroke; it is a sampling artifact of the instant the slot closes and that one row is not read.

7. Open questions, each with why it is here and whether we can run it

The questions below are the ones the paper leaves open. Each says why it matters, what would answer it, and whether the answer is within this programme's means. The ones that could be run before publishing were run; their results are in sections 1 and 4.

Is the station-keeping a true hover? At half a millimetre the valved bell's per-cycle displacement stays inside the floor band but changes sign (+0.046, +0.066, +0.009 R against -0.021, -0.089, -0.026 at one millimetre); the residual drift is below what the instrument resolves, and a quarter-millimetre run or a better body coupling is the artifact that would settle it. *Is the phase line resolved?* The slope is (-0.37 versus -0.33 R per period across the two grids); the offset is not (three hundredths of a radius between grids); the free bell's first-cycle displacement itself halves from one millimetre to half a millimetre, so every free-body displacement of the 40/60 stroke in this paper carries an uncertainty of a few hundredths of a radius. *Is the Stokes floor the rasterisation of the body mask?* Partly tested: the rasteriser's search reach doubled reproduces the floor to the digit, and halved below the mask's band breaks the mask outright, so the reach is not the floor; the band itself (2.5 mm plus a 3 mm smoothing) is the knob that would answer it, and it is not exposed in the tool of record. The suspect that remains is the first-order body coupling, the same suspect as the free-body resolution sensitivity. *Does our eight-percent recapture share match a measured animal?* Needs the published frame data of Gemmell, Costello and collaborators beside our stroke ratio and Reynolds number; a comparison, not a run. *What is the core pressure by a real Poisson solve?* A scalar-Laplacian solver on this grid; the closed-form Lamb-Oseen value is printed in its place. *Can the duct mode be declared from the cap rather than inferred from the mouth?* Two printed columns, the cap's open fraction and the apex flux; cheap; not yet. *Does a Tesla valve's diodicity degrade station-keeping by its ratio?* Run: a directional leak of 0.3 in the closed cap moves the per-cycle displacement by one to three hundredths of a radius against the no-leak record, inside the resolution band; not degraded by its ratio within what the instrument resolves, and not refuted below it. *Does an iris at the mouth raise the formation number?* Run, and null by geometry: an iris closing to 0.7 R reproduces the no-iris run to the last digit because the folding lip already closes the mouth to about a third of a radius; the lip is the iris, and a test needs the lip off or a closure past 0.66 R. *Can the duct be declared from the cap?* Run: yes; the cap's open fraction and apex inflow are now printed and section 1 reports them. *What spacing makes a staged leapfrog array fastest?* Three runs on the ring tool. *Can a vortex ring carry momentum to a body at a distance?* A receiver body in the ring tool. *Is the self-timer stable?* A linearised run. *Is nine hertz comfortable on a suit?* A wearer, not a simulation. *What are the material Q values?* A bench. *How does this instrument compare with the published axisymmetric hydromedusa solver of Sahin, Mohseni and Colin (2009)?* A comparison at the level of their published swimming velocities and vortex pictures; not done; the most direct outside check available to this paper.

8. Tests a reader can perform

Every test below is a Python model with a fidelity tag; the design ledger is the map. Added mass β is closed analytically (Lamb's disc, $\beta = 0.85$ upper bound; the 0.65 used in the scan was low, speeds fall ~13%). Self-timing is simulated: the pressure-triggered kick locks at every Q and quantises the rest to whole resonance cycles (jelly_self_timer_sim.py). The ring-body interaction is simulated (§7). Pair matching is priced and shown to be the wrong architecture; the two-stroke null replaces it. Stages 1, 2, 3, 5, 6, 6b and 7 of the staged rebuild are done (§7A), viscous stages 0 and 1 (§7A), and the viscous stage 2 ladder planned in The viscous stage-2 plan is built and closed through rung 6 (§7A): the grid, the wall at two viscosities, the tethered bell, swirl, the free body, and the animal's stroke. Stage 4, the multi-cycle run, is now the free body's normal case. For the swimmer the viscous axisymmetric solver is the tool of record; the inviscid family stays the reference it was validated against. Owed in order on the viscous side: the the half-millimetre check of the slow return is done (sign confirmed, magnitude $2.4\times$, not converged — 0.25 mm would be a week); the mirror strokes at both viscosities (the parity test of the holonomy question); the leash case — refill geometry as masks on rung 6, tethered, at 1 mm and then 0.5 mm; the slow return at duty 0.1 and the cavity profile; the passive flap coupled implicitly, as its own piece; and the checkpoint deposit of this stage with its limits stated loudly — first-order coupling, axisymmetry, resolution tags. The kernel re-runs and the edge sweep are done (§7A); Hoover et al. 2021 is read in full (§7B). Not yet done on the inviscid side: the stopping vortex's circulation converged in its own right (its 20% spread stands), and the per-panel vorticity budget (Q7) as the cheap attempt at secondary rings. The stage-2 plan's revision b carries the wall notes — the boundary-layer thickness that sets the grid (1 mm at water viscosity, finer than the morning plan's cell), the operator's 1% circulation cost as the noise floor for any wall sink, the implicit penalty step, and rung-1 pass numbers taken from the v5 run. Then the viscous solver, for which the architecture is now named — Rasmussen, Rosinelli, Storti, Koumoutsakos & Walther (arXiv 0910.3242, 2009, abstract) simulate a reconstructed jellyfish with viscous vortex PARTICLES and Brinkman PENALIZATION for the body, the same family as the blob-ring model here, with viscosity by particle strength exchange; their stroke A sheds two rings per cycle, stroke B three, and speed scales as $\sqrt{\text{Re}}$ at fixed kinematics. Two 2-D tools are noted with their caveat: IB2d (Battista et al., named by Taheri, IOSR-JMCE 2018) is an open-source immersed-boundary FSI code with a Python version, and Dawoodian, Sau & Dadvand (Appl. Math. Modelling 95, 2021, OCR full text) run a 2-D lattice-Boltzmann bell at Re 70-400 finding that recapture is a Reynolds-dependent gift (oblate bells have the higher cost of transport at low Re and the lower at high Re) and that higher bending rigidity raises cost of transport for every shape — the same direction as the stiff-skin result of §2.3 from an independent method. Both are Cartesian 2-D, so their "rings" are vortex pairs and the axisymmetric physics — dilation, formation number — is lost; useful for a first viscous look at shedding on a body, not for the ring. A 3-D filament code for swirl steering (O3) stays after these; a cheap same-sign two-ring spacing sweep for the array leapfrog can run any time.

Bench-form of the same tests, for whoever has a tank:

1. Added-mass β — plate, tank, stopwatch (design-relevant: speed 0.7-1.7 m/s across β 0.3-2).
2. Thickness/tension sweep at fixed diameter, speed and thrust recorded separately. 3 + 8. Ring-body bench (jelly_ring_body_bench.py): 5 cm piston-cylinder ring at L/d 3.6, Re 3000, spheres D/d 0.5/1/2 on-axis and offset, drives m = 0 and m = 3; PIV both planes, skin shear and pressure, hydrophone null; 12 runs $\times$ 5. Predictions: zero helicity for m = 0, non-zero for m = 3; peak shear at collision; secondary strength falls with D/d.
3. Formation-number wall: fixed volume, nozzle swept so FN runs 0.3-6; impulse plateaus near 4; hydrophone RMS per unit impulse rises below 0.3.
4. Self-timing: pressure-triggered stroke vs clocked, cost of transport compared.
5. Spring Q ring-down in air and water; target Q $\geq$ 100.
6. Antiphase pair: source level of one bell vs pair at d = 2L; prediction -38 dB at 1 m scale.
7. Travelling-mode torque: yaw rate vs mode amplitude; prediction $\propto m\cdot A^2$.
8. The phase test — RUN, PASSED: five points on a line, zero crossing near 0.095 T; see §7A.x. As written: Run the 40/60 swimmer with a pause of 0.1, 0.2, 0.3 and 0.4 T before its second stroke and read the second cycle's displacement. The prediction is a smooth curve through +0.031 at zero pause and -0.002 at 0.10 T with a zero crossing before 0.15 T. A flat curve falsifies the memory reading and restores the propulsion one.

9. What kind of work this is

Most of the walls found in §7A were defects in this program's own solver, not discoveries about jellyfish: the leaking apex, the Kelvin closure, the double-counted inertia, the under-diffusing exchange constant. That is the cost of a choice — to build the flow solver here, in pure Python, reproducible from a batch file, with no bench — rather than to run a jellyfish through an existing immersed-boundary CFD code as the field does (Hoover, Dawoodian, Kang). In a mature field prior art leads until the tool is trusted, and the tool is now trusted for everything that is not recapture. The results that are new are about the machine, not the animal: the phase lever, the recoil accounting, the edge thickness as a design parameter, the pump-versus-swimmer fork. If the swimmer's pricing comes to matter more than owning the tool, the honest alternative is to run an open immersed-boundary solver as the reference and validate this light tool against it; that is a strategic choice and it is recorded here as one. Four lessons are recorded here because they are the kind that recur. Two are about reading: a prediction is scored against what was written before the run, in the run's units, and a partial hit is reported as partial; and a number filed for a run comes from the run file on disk, read by a tool — when four results arrived as text after an upload failed, every one of the four inline readings was

wrong in at least one number, and the file caught it. Two are about the tool. Three batch files were launched against a tool file that had not yet been replaced; the tool ignored the arguments it did not know and ran the wrong case silently, and the failure was found by reading the output's header line. The rule now is one tool version per run day, a manifest check before any launch, and a launcher that refuses to start if the tool's hash is wrong. And the time step had been set from the whole run's length, so runs of different cycle counts used slightly different steps and diverged by a hundredth of a radius by the second cycle; it is now set per cycle. A fifth lesson, a gate is a claim about a file and is tested on the file the machine actually writes. A launcher's check read the fidelity output with a tool that cannot read the encoding the laptop writes, and refused a run that had passed; two hours of idle laptop, and the fix was to test the gate on the laptop's own file rather than the workshop's. The viscous rungs move the balance: the light tool now hosts the wall, the parked vortex and a free body that swims with the animal's stroke, and its cost per finding is known — about fifty times that of the integer instruments elsewhere in this program, with the laptop in the critical path.

Appendix A — The speculative-engineering programme that framed the measurements

This appendix is the design work of April to September 2026, kept whole. It predates and surrounds the instrument; its numbers are estimates unless a section 4 run stands behind them, and it is here so that nothing the programme did is lost.

1. The proposal as originally written

The bell is a resonant structure contracting at its natural frequency; each contraction sheds a leading vortex ring and the passive refill sheds a trailing ring that pushes back — two pulses per beat, the animal surfing its own wake. Jellyfish operate at Strouhal 0.2–0.4, the band shared by fish, birds and dolphins. Applications: a dielectric-elastomer diver suit of resonant rings; a hull terminating in nested annular bells fired as a phased array of rings, steered by phase, hovering by standing waves. Pre-registration: a 0.5 m annular resonator on and off resonance, predicting 40%+ more circulation per unit energy on resonance. Acoustic silence in the 2–200 kHz band named as the prerequisite for approaching a dolphin pod.

2. The analysis of record, as it stands

2.1 Strouhal holds. Aurelia at 0.10 m, 1 Hz, 0.02 m excursion, 0.06 m/s gives $St = 0.33$.

2.2 Size-invariance holds; the pin is material-and-thickness

Two physical models with the water's added mass and a strain-limited excursion replace the old membrane law (jelly_hL_scan.py). In both, speed at fixed material and fixed wall-to- diameter ratio is identical at 0.1, 1 and 3 m: **bigger does not go faster**. But wall thickness, or equivalently hoop tension in a thin skin, is a lever the old law hid. With 1 MPa silicone, speed runs from 0.04 m/s at a wall 1% of diameter to 1.2 m/s at 10%, and a 3 cm tensioned skin on a 1 m bell reaches the same 1.2 m/s under about 14 kN of hoop pull. The plate model reproduces Aurelia without tuning (0.85 Hz, 0.04 m/s against 1 Hz, 0.06).

2.3 The fast bell is closed twice

Stiffer skins post higher nominal speeds, but the ejected slug becomes shorter than about a fifth of the nozzle diameter (formation number below 0.3) and no ring forms; the bell becomes an acoustic radiator. The acoustic model says the same thing louder: at a fixed ejected volume, radiated sound scales as frequency to the fourth, so a 1 m bell radiates 7 W at 2.6 Hz, 1.5 kW at 10 Hz and 460 kW at 42 Hz. **The ring-shedding bell tops out near 1-2 m/s at any size; everything above is noise.**

2.4 Two cruise regimes, both size-invariant

Recapture needs the stopping vortex to roll up before the next stroke, and at the 1.2 m/s geometry that takes 1.43 cycle periods at every size (jelly_self_timing.py). So there are two modes: **~0.84 m/s with a 50% rest duty and recapture — the jellyfish mode, best cost of transport — and ~1.2 m/s without — the squid mode**. A separate valved intake ring (author's design, §4) is the hardware of the squid mode; closing it is the jellyfish mode. The hydromedusa *Aglantha digitale* carries exactly this two-mode arrangement in one muscle via two nerve impulse types (a claim from the neurobiology of *Aglantha* that this paper has not checked against a publisher record and does not rely on). The jellyfish mode's advantage now has a second measurement behind it: Gemmell et al. (*Proc. R. Soc. B* 2021, full text on hand) report +41% maximum speed and +61% distance per cycle for Aurelia when the stopping vortex is present, alongside the 30%/48% of Gemmell 2013.

2.5 The verdict

Primary propulsion for a slow vehicle at 0.8–1.2 m/s (1.6–2.3 kn), and station-keeping below that, with thrust that scales with skin area. The large bell is a silent tug: a 10 m bell gives ~70 kN at 1.2 m/s for ~140 kW. The fast vehicle stays dead. "Silent" is now precisely stated: silent above ~10 Hz, and an infrasonic monopole below it unless cured by one of the two routes in §6.

The verdict carries a floor: the instrument's reciprocal known-answer test moves 0.085 R per cycle where physics moves zero (§7A, §11), so any per-cycle displacement smaller than that is not read.

3. Findings closed

48%. Gemmell et al. (PNAS 2013): passive recapture carries the animal 30% further per cycle and cuts cost of transport by 48%. Jellyfish Froude efficiency is 0.09–0.53 against ~0.8 for fish. Not a Froude figure; the old "48% Froude" was a conflation.

Prior art, abstract level. Bujard, Giorgio-Serchi & Weymouth (*Sci. Robotics* 2021): rib-and-membrane bell at resonance, one body length per second, 10–50× small-propeller efficiency. Hoover & Miller 2015; Hoover, Porras & Miller (*JFM* 2019). The resonance claim is demonstrated, and it validates the mechanism.

The virtual wall. Gemmell, Du Clos, Colin, Sutherland & Costello (*Proc. R. Soc. B* 288: 20202494, 2021) name the recapture mechanism: the stopping vortex parked under the bell acts as the image vortex of a wall, so the animal swims in ground effect in open water. Measured on Aurelia by PIV and pressure fields: peak positive margin pressure 0.74 Pa with the stopping vortex against 0.32 Pa without (2.3×), thrust from that pressure 2.7× greater, swim speeds 18–26 mm/s. The word "wall" carries the physics — a wall is something the bell margin pushes against, which matters for what a ring-only model can and cannot reproduce (§7).

Pulsejet. Pulsed-jet Froude efficiency is $2/(1 + u_{\text{jet}}/U)$. The bell keeps $u_{\text{jet}} \approx 1.8U$ (≈ 0.7); the Argus pulsejet is the same engine with the ratio ruined. Its lesson is self-timing.

Ring-body interaction (papers supplied by the author). Chen, Gao & Chen (*PRF* 7, 044703, 2022, abstract): a sphere in a ring's path spawns secondary and tertiary rings whose strength depends on the sphere-to-ring diameter ratio; stroke ratio 3.6. New, Xu & Shi (*Phys. Fluids* 36, 054101, 2024, full text, abstract and introduction read): at Re 3000 the primary ring gives peak skin friction at collision; secondary rings entangle around the primary. Dora et al. (PIV09, 2009): strong ring sound needs compressibility, Mach > 1.

Comb jelly. The author's movie shows a lobate ctenophore: ciliary metachronal propulsion, no rings, no resonance, hydrodynamic stealth (Colin, Costello, Hansson, Titelman and Dabiri 2010, *Proc. Natl. Acad. Sci.* 107(40):17223–17227, doi 10.1073/pnas.1003170107; read at abstract level). Each ctene at Re ~ 1 is a Shapere-Wilczek swimmer: displacement per stroke is a holonomy over shape space (Shapere and Wilczek 1989, *J. Fluid Mech.* 198:557–585; publisher record checked). The comb row is the coherent limit of the author's dial machine.

Helicity. Fluid helicity $\int \mathbf{v} \cdot \boldsymbol{\omega} \, dV$ is the abelian Chern–Simons functional (Moffatt 1969; Arnold). A single unlinked swirl-free ring carries none; coaxial recapture is a linear- momentum refund. Swirl or linking is required for angular momentum — and a travelling rim mode supplies swirl on demand (§5).

Media. Ported by Strouhal and formation number, both medium-blind. Cold/Europan water: viscosity $\times 1.7$, irrelevant above ~ 1 m. Jupiter 1 bar (ρ 0.17): rings form, a lifting-body problem. Ionosphere: Knudsen $\gg 1$, no rings. Vacuum: a pulsed thruster with a free valve.

4. The engine (author’s tube-and-torus design, 8 September)

A tube carries a slug on a spring; a torus riding the tube squeezes a ballute that expels through a valved throat; inner and outer volumes are a two-stroke’s two chambers; a zipper rail runs the squeeze crown-to-rim; no rotating parts.

Priced (jelly_slug_engine.py, 1 m bell, 15 cm stroke): the resonance lives in the spring, so frequency is a design choice. **The slug’s mass buys nothing** — thrust, speed and power are identical at 0, 50 and 200 kg because the 262 kg of water added mass is the flywheel; the slug is a light magnetic coupler. At 2 Hz: ~ 400 N at 0.9 m/s for ~ 800 W electrical, with the actuator supplying $\sim 5\%$ of the 7.3 kN peak spring force. Power scales as f^3 .

Spring (jelly_spring_q.py): the spring must have $Q \geq \sim 100$ to waste no more than a fifth of the useful work. Steel and canned repelling magnets pass; a cold gas pocket is marginal; warm gas, elastomer and a buoyancy float lose more than they deliver — which is why the animal has muscle, and why the float is a harvester not a spring. Quadrature drive needs two resonators matched to f/Q (13 mHz at Q 150), so the spring must be tunable: the magnetic spring’s bias-coil tunability is its real advantage. Ring-down bench: $Q = \pi N / \ln(A_0/A_N)$.

Depth: ring and skin are pressure-blind; a gas-pocket spring is not (0.3 m³ at 100 m, 3 m³ at 1000 m, 12 m³ at 4000 m for the same k). A gas pocket is also 328 kg of lift per 320 L and a store — spring, bladder and battery in one volume, with the glider’s buoyancy-instability control problem attached.

Author’s mechanisms: umbrella ratchet = a top-dead-centre latch for the recapture pause — made unnecessary by the self-timer result (§2.4: the pressure trigger quantises the rest to whole resonance cycles by itself); ratchet armatures = rectifier = two-stroke valves; D12 pentagon ballute with edge chords = breathing polyhedron (Hoberman, Fuller), which as a closed body is an acoustic monopole with zero thrust and needs one face removed as the nozzle; momentum-recovery ring = the velum, keep as drawn; separate one-way intake ring = squid mode (§2.4); Coanda wall jets on the exumbrella for station-keeping = valid in water, thrust-per-watt $2/u_{jet}$ favours gentle wide jets, fed by the same engine at low amplitude, with the caution that they alter the margin separation that forms the stopping vortex.

5. Arrays, control and power

The gearbox. One stroke energy, routed by mode: $m = 0$ to volume (thrust, and the monopole); a travelling $m \geq 1$ to torque (steering, volume-neutral, no monopole); a standing $m \geq 1$ to neither — energy cycling in the spring, a quiet idle that keeps the resonator hot. Gear changes are phase changes between two actuator channels; shifting costs no mechanism. Every $m \geq 1$ mode is volume-neutral, so hovering in gear radiates only the lobes’ higher poles. Sensor placement follows the Chladni nodes of the mode in use.

OAM channel (jelly_oam_torque.py). A travelling rim mode $\cos(m\theta - \omega t)$ is two standing modes in quadrature; its Stokes drift puts swirl on the ejected slug and reaction torque on the vehicle. Mode 3 at 5 cm amplitude on the 2 Hz bell: ~ 23 N·m, 90° yaw from rest in ~ 3 s on a 300 kg vehicle; mode 5 at 10 cm: 150 N·m. The animal’s version (Hoover et al. 2021) says the mode’s phase speed must sit near the skin’s elastic wave speed $\sqrt{E/\rho}$ for the margin to hyperextend — 0.32 m/s for 100 Pa mesoglea, ~ 30 m/s for a 1 MPa elastomer skin — which for a 1 m bell means a circumferential transit of ~ 0.1 s and pins the drive frequency of any tuned rim mode to the skin’s modulus (held as a number for jelly_oam_torque). Prior art in structure: the travelling-wave ultrasonic motor, with water as the rotor. Two bells at $+m$ and $-m$ net zero angular momentum; their amplitude difference is the yaw command. A ring of N bells is circulant, so the array’s modes are its Fourier modes and phasing selects m ; each channel has one Laplace pole at the engine’s resonance.

Matriarch and daughters (jelly_matriarch_budget.py). A one-wavelength surface chain (156 m at 10 s) in 1 m seas at capture-width 0.1 harvests ~ 38 kW electrical: ~ 48 daughters cruising or ~ 380 station-keeping; half-metre seas ~ 10 kW; storms scale as H^2 . Daughters below $\sim 2/3$ hang in quiet water (13% of surface motion at 50 m). A deep air store holds 0.74 kWh/m³ at 100 m; a 24 h calm costs 3.3 m³ per station-keeping daughter. The chain is the fleet’s one exposed, radiating, storm-vulnerable element: deployable/retractable is a requirement. Deep-current rotors: nothing in abyssal water (< 1 W/m²), 150–520 W/m² in boundary currents and strong eddies, in counter-rotating pairs. Storm option: lower the chain to 75 m and 6 m seas feel like 0.7 m.

Propulsion sort. The quiet propulsors are those whose push speed sits near the vehicle speed, and every one is slow: bells, undulating fins, cilia. Above ~ 2 m/s everything radiates a blade or a jet. MHD is silent and a few percent efficient in seawater. The open design space: bell for impulse and hover, travelling-wave skin for the silent creep, glider ballast for transit, nothing rotating.

6. Acoustics — the null and its price (jelly_acoustic_null.py)

A bell whose volume pulses is a monopole at its stroke frequency, radiating $\rho \omega^2 Q^2 / 8\pi c$. At 1.2 m/s cruise geometry: 15 cm handheld 0.16 W, 163 dB re 1 μ Pa at 1 m; 1 m bell 7 W, 179 dB; 2 m volume 27 W, 185 dB; 10 m tug 670 W, 199 dB — ship-class source levels, all infrasonic (0.3–18 Hz). Against the microseism floor (dominant below 5 Hz, peaking near 0.17 Hz; ~ 95 dB re 1 μ Pa²/Hz at 2–3 Hz and ~ 130 near the peak, read from Wenz-class curves, ASSUMED values on a SOURCED shape) a single 1 m bell meets ambient at ~ 160 km — a treaty-hydrophone source. Two cures:

Route A, the antiphase pair. Two bells two diameters apart form a dipole, power $\times (kd)^2/3$, ~ 38 dB, detection range ~ 2 km. But the ~ 38 dB is a floor that needs the two bells matched to 1.3% in amplitude and 0.7° in phase, and a resonator’s phase moves by $\text{atan}(2Q6)$ with detuning, so at Q 150 the two spring frequencies must agree within 41 ppm. **Efficiency and matchability pull on the same knob.** A k-tuning loop was simulated (3% mismatch, Q 120–150): 74° phase error open-loop; the loop must hold tens of ppm. Wrong architecture for the null; recorded so it is not re-derived.

Route B, the two-stroke’s intrinsic null. The engine as drawn is a piston between two water chambers, one venting through the nozzle while the other fills through the intake ring; external volume flux is zero at every instant, so the monopole vanishes by construction with no matching. Remaining: a dipole from ports $\sim L$ apart (~ 44 dB at any size) and a residual from skin compliance (1% of stroke $\rightarrow -40$ dB; 5% $\rightarrow -26$ dB). Skin compliance is the acoustic spec: stiff chambers, soft nozzle. The intake ring that forfeited recapture buys the null for free.

The trade is stated and left: jellyfish mode (recapture, best CoT) is a monopole needing the 41-ppm pair; squid mode (intake ring, no recapture) is intrinsically null. The 10 m tug’s 0.26 Hz sits on the microseism peak and hides there even unpaired (~ 28 km), paired ~ 350 m. Shallow operation self-cancels against the surface (~ 18 dB at 10 m for 2.6 Hz). Aurelia radiates $\sim 10^{-7}$ W: the animal is quiet because it is small, not because bells are silent.

7. Sensing

The bell as a mechanoreceptor (author’s “radome”): a standing ring at the mouth is disturbed or broken by a body passing beneath, and the skin that shed it reads the change as shear and near-field pressure — peak at collision, secondary-ring strength falling with intruder size (Chen; New). Vortex sound at Mach 10^{-3} is negligible, so the bell is a poor microphone and a fine mechanoreceptor, the ctenophore’s stealth-predation logic run in reverse. The same skin signal is the self-timer for the recapture stroke (§2.4). Bench and field scales differ by 10^3 in pressure (0.3 Pa vs ~ 1 kPa), so the field skin sensor is specified near 10 Pa.

The sensing chain, simulated (jelly_vortex_ring_body.py and its drivers — axisymmetric inviscid blob-ring plus a sphere by submerged source-ring panels; free-ring speed 0.89 of Saffman, impulse conserved to 0.01%; pressure by the unsteady Bernoulli equation with $\partial\phi/\partial t$ as the path integral of fluid acceleration from the quiet far field). Four observables, in order of strength, all read against what the ring was going to do anyway:

What the intruder feels. Its nose pressure rises to ~ 3.8 dynamic pressures on approach and its equator sees suction of 7, 10 and 19 dynamic pressures as the ring squeezes past, for intruders of half, one and two ring diameters. Peak wall slip $47 \rightarrow 67$ mm/s at the equator half a second after closest approach —

New's timing. The intruder-side signature grows monotonically with size.

Ring dilation. 6% → 33% → 117% for the same three sizes, with the ring slowing to 0.88 → 0.71 of its free speed. **The skin need not resolve the intruder; the ring's dilation is a size gauge.** Food-versus-threat is a threshold on dilation.

Rim pressure as deviation (the still-ghost). A sensor just outside the ring's birthplace, read as the difference from the expected free-ring trace: the two-diameter intruder gives a 57 mPa deviation — SNR 31 against the 10 Pa field spec at 1 m-bell scale — peaking 2.7 s BEFORE closest approach, early warning; the ring-sized intruder 4 mPa, marginal; the small one nothing but an 8 mPa static reflection at launch. The signature decays with distance from the interaction, so a skin on the crown four radii back sees only large intruders; the sensor belongs at the rim.

The pacemaker (the beat that did not come). Over the approach the intruder delays the ring's arrival by 0.7 / 1.4 / 3.6%; the self-timer skips a beat only when that delay pushes the rest over a whole-cycle edge, so sensitivity is set by how close the design rest sits under the edge: at 1.95 cycles it catches the large intruder with a 2.6% margin, at 1.98 it catches the ring-sized one but sits inside a 2% timing jitter — false alarms. A weak, free confirmer for large intruders. The threshold trade, named: parking the pacemaker just under an edge buys sensitivity and pays in false alarms — the trade every sensory neuron makes by resting near threshold. Nature's pacemaker sits there for this reason.

The wall in the model. It is inviscid, so it cannot bear the secondary and tertiary rings Chen and New observed. A shedding shortcut was tried — release the wall's slip as counter-rotating blobs where the flow decelerates — and it put vorticity of the right sign in the right place but fed on itself: 50–80% of the primary's circulation shed regardless of the allowed fraction, the primary stalled unphysically, no compact roll-up. The missing physics is the boundary layer's finite vorticity budget and regeneration time. NO SALVAGE as a quantitative tool; the fluid mechanics is primary and the next build is a viscous axisymmetric vorticity-streamfunction solver with the sphere as an immersed boundary. A per-panel vorticity budget with a regeneration clock is one cheap attempt worth making first.

A second wall in the model — the virtual wall does not appear without the bell. The two-ring run (jelly_virtual_wall.py, bench scale R = 5 cm, probe at the subumbrellar margin point) asked the ring model for Gemmell's 2.3× pressure rise by parking a counter-rotating stopping vortex inside the margin. It got the opposite: at half the primary's strength the margin peak pressure fell to 0.76× of the ring-alone value and the probe went into suction; at full strength the peak itself went negative and the primary slowed to 0.79 of its free speed (0.92 at half strength, against 0.89 alone). The reason is in Gemmell's title. The stopping vortex is a wall for the BELL to push against; the pressure rise is a moving-boundary interaction between margin and vortex, and a model with rings and no bell has nothing to press. NO SALVAGE as a ring-ring effect; recorded so it is not re-derived. What the run did give is the first array number: a same-sign ring at half strength inside the margin raises the primary's early speed by 31% (1.31 of Saffman against 0.89) and the margin pressure 1.74× — the leapfrog of a staged array; a counter ring one diameter behind, a neighbour bell's ring, changes little (1.14×). A scale check passed on the way: Aurelia's measured margin pressures are 0.3–0.7 Pa, and the inviscid bench ring at similar circulation gives 0.1–0.3 Pa at the skin and 0.4–2 Pa on the body — the same order. The next build follows from the wall: put the bell into the existing panel method as a moving axisymmetric body with prescribed Aurelia margin kinematics and a wall-velocity boundary condition, so the stopping vortex has a wall to be. The same build sheds the starting vortex from the moving margin, which supplies ring formation (O4) for free.

The kernel under everything, swept (jelly_ring_kernel_sweep.py). Every flow model in this file inherits one blob-ring kernel, validated once at one setting and never varied. Twenty-seven runs — core smoothing σ at 0.25, 0.5 and 1.0 of the core radius, 13, 25 and 57 blobs, time step 0.02, 0.01 and 0.005 R/U, each carried ten radii — settle it. The time step is converged: the speed ratio is identical to three decimals down every dt column and impulse and energy drift fall a hundredfold per two halvings. The smoothing and blob count are not: at $\sigma = 0.25a$ the ratio climbs 0.894, 0.956, 0.973 with 13, 25, 57 blobs and is still rising toward about 0.98; at the production setting ($\sigma = 0.5a$, 25 blobs) it is 0.899; at $\sigma = a$ it sits near 0.75–0.79. The 0.89 of Saffman that every ring-body result carries was a two-parameter discretisation value, not a price of smoothing, and moving either parameter moves the ring's speed by up to a quarter. The core's second moment also grows 2–24% over ten radii. **Every ring-body speed, timing and pressure in this file carries roughly a 10% speed bias at the production setting, and is flagged so until re-run at $\sigma = 0.25a$ with at least 57 blobs.**

The bell as a moving body — built, unstable, recorded (jelly_bell_body.py). The build named above was made: an oblate cap carried as a bound vortex sheet of 24 ring vortices, the margin contracting 20% at 1 Hz with a 40% contraction duty, tethered, a Kutta margin releasing one free ring per step. It forms both rings on its own. Over three clean cycles the wake impulse per cycle rose 0.74, 1.15, 1.50 mN·s — thrust with the stopping vortex present 2.04 times the first pulse's, against Gemmell's measured 2.7 — with a 43–47 mm/s jet, the starting ring at about (0.94R, +0.25R) and the stopping vortex at about (0.88R, +0.2R), just outside the mouth rather than inside the cavity where the ring-only runs had assumed it. Two things are recorded from the build. The first is a wall: closing the system with Kelvin's theorem, total circulation zero, the standard two-dimensional lumped-vortex closure, produced a negative starting ring, because meridional circulation is not conserved in axisymmetric flow — a single ring has non-zero total circulation — and the apex ring of vanishing radius silently absorbed the constraint. A Kutta margin with no bound vorticity on the edge panel, the free ring solved as an unknown, replaces it. The second is a failure of the inviscid panel method, not of the physics: at cycle four the impulse jumped sixty-fold and the jet to 390 mm/s, and every intervention tried; this is the familiar behaviour of a vortex-sheet panel method whose free ring is advected without a viscous core — a numerical instability with a long literature, not a geometric route to a hypervelocity jet, and it is why the inviscid instrument was retired — a wall-reflection guard, a larger wake core, a uniformly larger core — changed cycle one, the cycle that had been working. Twenty-four panels was a cost choice, and five other lengths were set as fractions of that one. The script ships as a work in progress, not a tool of record, so the thread is not lost; the rebuild is staged in §9.

Sensors sit on the Chladni nodes of the mode in use, where the skin reads the fluid and not the stroke. Detection logic is the ghost detector's: the winding-ghost is circulation that persists, the still-ghost is a trace that stops changing while the field churns.

7D. The author's frames

The build up to rung 5a had been swimming a shape nobody had looked at: a bell that squeezes radially at fixed height through an open mouth. The author's stop-motion frames from locomotion video — a sea nettle from the side and from below (video: <https://www.youtube.com/watch?v=iGrShJO6t90>), a moon jelly (video: <https://share.google/BBzgOmFrQRIvqGwD>) from the side, with his own labels on the stills — are deposited with this paper as the file BEAR_FRAMES_20260911 (the author's frame sheets) and read as follows. The nettle's margin is scalloped into lappets, thin muscle-free tongues, with the tentacles rooted in the clefts between them and the rhopalial, the sense organs and swimming pacemakers, at the base of the clefts; the coronal muscle band stops inboard of the lappets, so the clock and the sensors sit at the hinge and the actuator one band inboard. From below, the mouth is not an open aperture: the oral arms fill most of the cavity and the jet leaves through an annulus between the arms and the margin, so the ring is born at the rim's radius with the arms as the slot's inner wall. Through the cycle the bell goes oblate to prolate, deepening as it narrows, the margin curling in under the rim with the lappets tucked into a thick rounded lip until the annular slot is nearly shut — a mechanical pinch-off that cuts the shed sheet when the animal chooses rather than when the formation number decides — and then flattening and widening with the lappets standing out as a fringe; three frames in, four out, the 40/60 duty that the tool had right. The moon jelly is a pure bell — shallow, oblate, no plug, no tail, a fringe of short tentacles that stream straight out behind in the push, tracing the annulus, and drift back in the refill. The author's labels on the moon-jelly still, read against the anatomy, give the spring: the dome is mesoglea, a collagen mesh mostly water with no muscle and no nerve, and the animal has one muscle direction and no relaxation muscle, so the whole return half of every cycle — refill, stopping vortex, lip opening — is powered by stored strain. His pink-chamber reading of the same animal: the inner chamber is about half the bell's height and stays so between relaxed and pulsed, the muscle pinches its base during the impulse and expels about eighty percent of it, and the dome springs slowly back to flat. Two anatomies, one requirement: a large fraction of a small cavity out through a rim that closes; the nettle fills the middle with arms, the moon jelly pinches. The rigid bell of rung 5a expelled 36% of a chamber the size of the whole bell, which is why it went nowhere. What the frames cannot give the axisymmetric tool is turning — the animals steer around each other by posturing the rim asymmetrically — and the slits between lappets as a distributed rim-level refill path; both are named as hypotheses for a tool that hosts them.

8. Use cases — how big (jelly_use_case_ladder.py; ASSUMED piston model)

Speed is fixed, so size is a thrust question and thrust scales with skin area. Handheld 15 cm bell: 16 N, 32 W at 17.6 Hz — low end of commercial diver units. Suit of four 30 cm rings: ~250 N, ~520 W at 8.8 Hz, comfort unknown. 1 m daughter: 700 N, 1.4 kW. 2 m observation module — the powered ultralight bathyscaphe: 2.8 kN, ~5.7 kW, steel or magnetic spring, bladder trim, paired for acoustics. 10 m tug: 70 kN, 143 kW. Platform 100 × 100 m, 5,000 t: buoyancy is 0.49 m of draft and no bell's business; loads 64 kN current + 240 kN wind (735 kN storm) → 7 × 10 m bells for operations at 1 MW peak, 18 for storm hold at 2.6 MW; prior art dynamic-positioning semi-subs and the ONR Mobile Offshore Base programme (a programme name recalled from memory; no publisher record checked; used here only as an example of scale). Habitat tug: a 4 m module moves at 0.47 m/s on two daughters, 1 m/s on nine; each daughter holds 71 kg of net weight dynamically — trim near neutral with ballast, let bells do the last metre per second, never the lift. The

inverted buoyant bell (siphonophore crown, Cassiopea pump) works with RIGID buoyancy only: a gas pocket sized as a spring makes 328 kg of lift at 100 m and 3 t at 1000 m for a 300 kg vehicle, with a negative stiffness of ~ 29 N/m of depth — NO SALVAGE for “spring pocket as float” below ~ 30 m; syntactic float plus tens of litres of gas trim is the way around. Where bells lose: lift, speed above 2 m/s, thrust per m^2 . Where they win: silence above 10 Hz, no rotors, thrust $\propto$ area, marine-life-safe positioning.

Appendix B — The instrument’s ladder, in detail

7A. The bell as a moving body, rebuilt in stages

The first bell-body build (§7) was set aside and rebuilt one verified stage at a time, each stage a script of record with its run file, each closing on a number with a known answer before the next feature went in. What follows is the result, and the four walls it found.

Stage 1 — the sheet alone. The bell as a bound sheet of lumped ring vortices solves to machine precision and leaks: with the cavity shrinking at $297 \text{ cm}^3/\text{s}$ the mouth draws $220\text{--}230 \text{ cm}^3/\text{s}$ IN and some $500 \text{ cm}^3/\text{s}$ leaves through the apex panel, at every panel count and both edge closures. A ring vortex of vanishing radius cannot close a surface on the axis — it can zero the flow at one point and nowhere else on the same panel. A point source behind the apex corrected the sign but needed $5\text{--}10 \text{ L/s}$ and would not converge. Distributed constant-strength vortex panels with the no-flow condition at every panel midpoint, apex included, closed the cap: mouth flux $296.3\text{--}297.9 \text{ cm}^3/\text{s}$ against a cavity rate of 297.1 , at both instants and all resolutions, and the jet at the mouth came out $22\text{--}25 \text{ mm/s}$ the right way. Everything after this stands on that representation.

Stage 2 — one contraction. A compact ring forms from the margin and leaves the mouth on its own; the wake impulse converges to 4% across panels, core and time step; the shed rate is smooth and turns negative while the margin decelerates — the stopping vortex beginning inside the contraction, as Gemmell and Dabiri see. The shed circulation would not converge (20% spread) because a sharp inviscid edge’s velocity depends on how the edge is treated.

Stage 3 — one full cycle, with a physical edge. The margin thickness was measured from Gemmell, Costello and Colin’s 2014 Fig. 2 (a 4 cm Aurelia with a 5 mm scale bar): the flexible flap is about 1 mm thick on a 40 mm bell, 2.5% of diameter, and about a tenth of a diameter long; scaled to this 100 mm bell the edge is 2.5 mm and the regularisation length half that, 1.25 mm, fixed regardless of resolution. With the release rate written as sheet strength times the speed the sheet leaves the edge, $(U_{\text{su}} - U_{\text{ex}})|U_{\text{su}} + U_{\text{ex}}|/2$ — the textbook squared form hides the sign in relaxation, and a first run shed positive circulation there — the starting ring’s circulation converged to 3% ($0.774, 0.798, 0.810 \times 10^{-3} \text{ m}^2/\text{s}$ at 16, 24, 36 panels), and the stopping vortex, forming after the end of contraction, ended the cycle under the bell just inside the margin by the flow alone, with a margin that does not bend. Its own circulation is not converged (20%) and remains held. And the cycle’s net impulse was negative: the starting ring, self-propelling at about 7 mm/s, was drawn back into the cavity by a refill of about 20 mm/s. A tethered bell eats its own ring; the animal swims away from it. Tethering changes the answer, so free swimming moved ahead of multi-cycle.

Stage 5 — free swimming. The body’s velocity follows from total momentum being zero in a fluid started from rest, body momentum plus fluid impulse, with the bound sheet’s impulse linear in the body velocity so that the added mass falls out of the same solve — 550 g on a 55 g body. The coupling checks pass (momentum residual 0.1–2%, mouth flux equal to the cavity rate in the body frame, velocity converged to under 2%). The bell oscillates and barely swims: 29 mm/s apex-first at peak contraction, a recoil to +15 mm/s in relaxation, one to two millimetres of net progress per second against 18–26 for a real 4 cm Aurelia, and the second cycle slower than the first.

Stage 6 — margin kinematics. A hinged flap on the outer fifth of the arc, swung inward through contraction and outward through relaxation at 30° or 60° , brackets Gemmell’s measured tip speeds (rigid 49/32, 30° flap 70/57, against 52/38 mm/s) and does not make the bell swim. The wall has a number in every run: the wake gains about 4 mN·s in contraction and loses 7–9 in relaxation. The stopping vortex parked under the bell carries more impulse than the starting ring — Neil and Askew measure three times the circulation on Catostylus — and an inviscid sheet keeps that circulation intact, so the body recoils onto its own ring by conservation of momentum. In the animal that vortex is pressed against the subumbrella, where a boundary layer cancels circulation at the wall and the flexible margin paddles on the high pressure it makes. Recapture is a vortex-wall interaction at boundary-layer scale, and no inviscid method can host it. The viscous solver on Rasmussen’s particle-plus-penalization architecture (§9) is therefore load-bearing for a swimmer.

The first build’s $2.04\times$ is withdrawn on three independent grounds: a leaking apex, tethering, and kinematics without a margin.

Stage 6b and 7 — the flap as the animal has it. Villanueva, Vlachos and Priya (PLoS ONE 2014, held in full) measured the Aurelia flap as the outer 17% of the arc, found it passive, and showed it lags the bell. Re-prescribed at 17% the flap’s lever turned out to be its phase, not its amplitude: a flap that merely trails the margin (180°) kills the rings and at 60° swims the bell backwards; a quarter-cycle lag is the best swimmer so far, three to four times the rigid cap, though still a third of a real Aurelia and still slower on the second cycle. Stage 7 then made the flap genuinely passive — a torsional spring-damper hinge driven by the fluid moment from the unsteady pressure jump across the sheet, with its added inertia (six times the tissue’s) taken from the same solve that gives the body its added mass — and the quarter-cycle lag appeared on its own whenever the flap’s natural frequency sat above the stroke’s. The reading of that lag was corrected on the afternoon of the 9th: a lightly damped oscillator driven well below its resonance follows its forcing in phase, not a quarter cycle behind it, and the run says the same — the lag barely moves between $f_{\text{n}}/f = 2$ and 4 (97° and 90°) where a resonance would swing it steeply. A stiff flap is quasi-static, $\phi \approx M_{\text{fluid}}/k$, so the lag it shows is the phase of the fluid moment itself, and that moment (ρ times the rate of change of the sheet’s cumulative circulation plus the tangential-velocity term, Katz & Plotkin) rides on the margin’s velocity and acceleration, a quarter to a half cycle from its position. The timing therefore comes from the water, not from the spring: stiffness sets the swing (91° down to 7° across the sweep) and the fluid sets the phase. That is a stronger design statement than the one it replaces — a tail stiff enough to stay above resonance has Gemmell’s timing for free and one knob left, its amplitude — and which of the two pressure-jump terms carries the quadrature is a print not yet made (held). The passive flap swims more slowly than the prescribed one because the prescribed sine kept swinging outward through late relaxation, where a passive flap has nothing to drive it; the animal’s late roll-out is therefore driven by something not in these kinematics — the bell’s elastic re-expansion or the stopping vortex under the margin — and that is an open falsification point, not a defect.

Kernel re-runs and the edge sweep. Re-run at the converged kernel setting, the ring-body family kept every verdict and changed the large-intruder magnitudes: dilation is robust to the digit, the half-size intruder still gives nothing, and the two-diameter intruder’s skin signal grows from 74 to 182 mPa of excess over baseline. The ring-only virtual-wall test was downgraded to unresolved: its probe sits within a core of the parked vortex, so its number is a near-field reading either way. And the margin’s edge thickness is decision-relevant for a machine: the shed circulations go roughly as one over the thickness, and a margin twice as thick nearly cancels the cycle’s recoil.

Viscous stage 0. One Gaussian-core ring on a lattice of blobs, with viscosity added as core spreading and as particle strength exchange, against the textbook core growth of $4\sqrt{t}$ — and an inviscid run of the same lattice as the baseline. The baseline is the finding: with no viscosity at all the core spreads by 2.4 times its area in seven radii of travel, because a Gaussian core on a ring this fat is not an equilibrium and an un-remeshed blob cloud disperses under its own strain. At this ring’s Reynolds number of 3000 the viscous growth is 40% of that and not separable from it. Where viscosity dominates (Reynolds 300 and 300) the operator is verified: core spreading exact, particle strength exchange converging on the law with the lattice. Remeshing is therefore the first stone of the viscous road, ahead of any wall.

Viscous stage 1 — remeshing, and the ruler it took to read it. The blob lattice is rebuilt every twenty steps with Monaghan’s M4’ kernel, which conserves circulation and impulse to a part in a hundred thousand per remesh, and the exchange operator was corrected to the axisymmetric form — the θ -component of the vector Laplacian, whose $(1/r)\partial/\partial r$ term the plane form omits and which is what conserves impulse. The first reading of the Reynolds-3000 case, run on the author’s laptop because it exceeds the build container, came back with an impossible width: a second moment weighted by signed circulation cancels the remesh fringe and stops measuring anything once fringe particles exist. Two rulers later — a half-circulation radius approximated from the particles, then the exact radius of the reconstructed field — the table reads cleanly. The approximate ruler’s over-reading was a constant, 1.28 for exchange-type spreading and 1.44 for core-width spreading, found by spreading a Gaussian core analytically and measuring it both ways; the number appeared four times identically in the laptop table before it was understood, which is how a ruler announces itself. With the exact ruler in the code, the author’s v5 run of the Reynolds-3000 case (his laptop, 10:35 on the 9th) read the table cleanly and closed it: remeshing at a lattice of a third of the core radius cuts the inviscid dispersion sixteen-fold (0.151 core areas in ten radii of travel against 2.36 unremeshed), impulse is held to seven parts in a hundred thousand, and the viscous excess over that baseline sits on the textbook law at every viscosity — 1.013 of $4\sqrt{t}$ at Reynolds 3000 with the axisymmetric exchange (0.962 with the plane one), 1.009 at 300, 0.968 at 30. The 20–25% deficit that the previous reading of this file carried at Reynolds 3000 was the old ruler’s constant, not physics, and the two candidates named for it are moot. What the run leaves to watch is a cost, not a defect: over the 374-step Reynolds-3000 case both

exchange kernels lose about one percent of total circulation, at about 3×10^{-5} per step, against a remesh cost of 5×10^{-5} per remesh; the axisymmetric exchange holds impulse three times better than the plane one (9×10^{-3} against 3×10^{-2}). That one percent is the operator's price and it becomes the noise floor for reading a wall's circulation sink (stage-2 plan, revision b). A last reading from the same table: the viscous rings at Reynolds 3000 travel at 0.98 of the thin-core speed for their instantaneous core, against 0.92 for the inviscid baseline — the viscous core has relaxed toward the equilibrium distribution the inviscid Gaussian never reaches.

Viscous stage 2, rung 1 — the grid, and what it was right about. The wall needs a grid under it, so the free ring was put on an axisymmetric vorticity-streamfunction grid in numpy (jelly viscous grid_rung1): the Poisson solve exact by a sine transform along the axis and one tridiagonal solve per mode in radius, vorticity carried in divergence form so total circulation is conserved to round-off, third-order upwind-biased fluxes, and the ring held at the domain's centre by rolling the field one cell at a time. It runs a millimetre grid at about 17 ms a step. It found one numerical wall of its own first: a plain central flux is unstable over a few thousand inviscid steps (the 10 R run grew the core 5.6 core areas and the speed to 1.36 of Saffman); the upwind-biased flux holds it, and the inviscid ring then travels ten radii with 0.038 core areas of growth, impulse to 7×10^{-4} and speed 0.987 of Saffman — better than the remeshed particles' 0.151. Conservation on the short cases is exact for circulation and 10^{-6} for impulse. Reynolds 30 passed outright (1.007 of the law). Reynolds 300 did not: the grid read 1.11 of the law at 1 mm and 1.12 at 0.5 mm, converged in grid and time step, where the particles read 1.009. Taken apart with advection switched off, the diffusion operator alone gives 0.997 in the planar limit and 1.033 on the ring, so three percent is the curvature of the axisymmetric operator and is physical; the remaining eight appears only when advection and diffusion act together. That left a ten-percent disagreement between two methods and one question: which was wrong about strain and diffusion in a ring core. The particle stage was given a lattice argument and the author ran the Reynolds-300 case at a lattice of a sixth of the core radius (81 minutes) and a quarter (12): the particles' excess moved $1.009 \rightarrow 1.063 \rightarrow 1.082$ as the lattice refined, extrapolating to 1.10-1.13, and their inviscid baseline fell $0.032 \rightarrow 0.012 \rightarrow 0.000$ to meet the grid's 0.017. The particles were under-resolved at their lattice of record and the grid was right. The physics of record is therefore that a Gaussian-core ring at $a/R = 0.2$ spreads about ten percent faster than the flat-vortex law, three from curvature and seven from its own strain working with viscosity; the stage-1 'excess near 1.01' is re-read as a coarse-lattice value — the operator was verified, the lattice was too coarse to show the strain term. Rung 1 passes, the grid is the tool of record for the wall, the particle kernel is the cross-check at a sixth of the core or finer, and every wall number will carry a resolution tag against the 1 mm boundary layer of the stage-2 plan. The grid's own Reynolds-3000 row, run on the author's laptop, completes the pattern: 1.007, 1.108 and 1.150 of the law at Reynolds 30, 300 and 3000 — the strain term growing with Reynolds number, as it should when the core spends more of its own strain time per unit of viscous time — with the same tag, ten cells per initial core at 1 mm and a half-millimetre check not yet run.

The disagreement, printed. Two methods sat ten percent apart on one number, and the number of record was reached by refining one method until it met the other: the particles' excess over the flat-vortex law walked $1.009 \rightarrow 1.063 \rightarrow 1.082$ as their lattice went from a third to a sixth of the core radius, extrapolating to 1.10-1.13, against the grid's 1.108 at 1 mm and 1.125 at 0.5 mm. That walk is the evidence that the converged 1.11 was tested rather than assumed, and it is kept in the record beside the answer for that reason. The same discipline applies to every wall number below: where a coarser and a finer run disagree, both numbers are printed, and the finer one carries the verdict with the size of the disagreement as its error bar.

Viscous stage 2, rung 2 — the wall. The same ring was launched four radii at a flat no-slip wall, the wall made by Brinkman penalization in its implicit vorticity form (jelly viscous grid_rung2 wall): the velocity inside a masked slab is relaxed to zero each step and the curl of that correction is added to the vorticity, which puts vorticity exactly where a wall makes it, at the mask's edge; every circulation and impulse total excludes the slab. Each case runs twice, free and walled, so the wall is read as a difference above the operator's own cost. The first laptop run exposed a defect in the control, not in the wall — the free run's totals excluded the slab too, so the free ring swimming through that region read a false stall and a false loss of circulation; corrected, the free ring holds its impulse to four places for 23 seconds, loses 6% of its circulation to physical cancellation at the axis as its core spreads to three centimetres, and slows from 14 to 7 mm/s as Saffman says a growing core must. Against that, at Reynolds 300 on the millimetre grid, the walled ring meets an opposite-sign sheet on the wall from the moment it starts (the approach flow's boundary layer, three percent of the ring), the secondary vortex grows from that sheet to 0.31 of the primary at one radius out and 0.57 at the stall, the ring swells from 1.00 to 1.38 R, the approach stalls at 0.784 R after about 21 seconds and turns to a slow rebound, and by the stall the wall has cancelled a third of the ring's circulation (0.61 remaining, against 0.95 free), 0.44 by the end. The sequence is Walker's and Orlandi's; the numbers are this program's at Reynolds 300 and carry a resolution tag — three cells per boundary layer, insensitive between 2 and 1 mm, with Reynolds 3000 waiting on a half-millimetre grid. The physics the inviscid sheet could not host — vorticity made at a no-slip surface and cancelled against it — is in the tool, priced. Rung 3 puts the bell itself in as the penalized body and asks the question the swimmer's design turns on: how fast the parked stopping vortex loses circulation against the subumbrella.

Rung 2 at water viscosity, half-millimetre grid (author's laptop, overnight 11-12 September, 1.8 h measured). The same launch at $\nu = 10^{-6}$ on an 801×1201 grid changes every column in the direction the physics says, and it resolves the bounce the Reynolds-300 run was too diffusive to reach. The free leg holds impulse to four places and loses 0.14% of its circulation in 23 s, so the operator's own cost at Reynolds 3000 is a rounding error and the walled leg's numbers are the wall's. The ring stalls at 0.39 R from the wall at 15.4 s (0.78 R at about 21 s in the tank), swollen to 1.55 R (1.38); the secondary vortex is 0.80 of the primary at the stall (0.57) and passes it, 1.05, by the end; and the primary still carries its full circulation at the stall (0.61 in the tank) and 0.80 of it at 23 s (0.50). After the stall it rebounds to 0.58 R at 18 s and approaches again to 0.40 R at 21.7 s — the first bounce of Walker's and Orlandi's sequence. The boundary layer at this interaction time is about 1.8 mm, so the tag is three to four cells per layer, the same class as the tank row at 1 mm. The number the swimmer needed: a vortex pressed against a no-slip surface at water viscosity keeps about eighty percent of its circulation over some seven ring-transit times, not half. The resolution walk between the two rows is printed rather than smoothed: stand-off $0.78 \rightarrow 0.39$ R, secondary $0.57 \rightarrow 0.80$, primary at stall $0.61 \rightarrow 1.00$.

Rung 3 — the bell keeps what it parks. The stage-3 shell (quarter-ellipse, $R = 5$ cm, $H = 0.8$ R, 20% contraction in 0.4 T, $T = 1$ s) went onto the grid as a moving penalized body of physical thickness 2.5 mm, tethered, from rest, one cycle and half a cycle of rest. Two build findings are recorded in the code and were bought by wrong answers: a shell thinner than a cell leaks, so the mask is at least a cell thick; and a single penalization pass leaks through a thin shell because the curl of a correction carries only its rotational part — iterated to a fixed point the mouth mass balance closes (0.84, 0.97, 0.99, 1.00 at 6, 20, 40, 80 passes), and the solver of record now does the penalization as one linear solve (GMRES, 30 matrix-vector products) instead of forty sweeps, six times faster, landing within 1-3% of every wake number the sweeps gave. One trap from that rebuild is kept as a standing lesson: a warm-started sweep tried in between double-counted the previous correction and produced wrong physics (wake circulation three to five times too large) while showing a better mass balance than the version it replaced — the mass-balance column alone would have passed it. The result of record (author's laptop, 9 September, Reynolds 300, 1 mm, three cells per layer): the stopping vortex forms in relaxation, peaks at -3.2×10^{-3} m²/s at 0.9 T, parks at (0.75 R, -0.09 R) under the bell — stage 3's place, at three times its circulation — and then, the body still, loses 29% of its circulation in the half-second of rest against the subumbrella, where a free ring on the same grid loses 6% in 23 s. At water viscosity, at both 1 mm and 0.5 mm, the parked vortex is stronger (-4.4 to -4.5×10^{-3}), sits inside stage 3's range, and loses about one percent in the same half-second. The wall's cancellation of the parked vortex scales with viscosity: a third per half-second in a tank at ten times water, almost nothing at the animal's own. At its own scale the bell keeps what it parks. The starting ring holds at $2.2\text{--}2.4 \times 10^{-3}$ across all three runs, three times stage 3's shed 0.81×10^{-3} : a viscous bell sheds its whole subumbrellar boundary layer, not just its edge, so the inviscid sheet under-counted the wake by a factor of three at every resolution.

Rung 4 — swirl, and a ring as a data channel. The azimuthal velocity was added as a third unknown, angular momentum $S = r^2 v$ carried in divergence form so its total is conserved to round-off, with the centrifugal term sourcing the meridional vorticity. The question was the encoding frame's: does a spin imprinted on a ring survive travel, and what does it cost. In the tank (Reynolds 300, 1 mm, four rings at swirl 0, $\frac{1}{4}$, $\frac{1}{2}$, 1 of the core speed, 33 s each): spin slows the ring, more with more spin — 1.046, 1.038, 1.014, 0.927 of Saffman at one radius, 5.77 to 5.34 R covered — there is no axisymmetric burst at any swirl because the core fattens 25-fold by viscosity whether it spins or not, and fat cores do not tear; the sign of the angular momentum is held in every case; and readability decays by the same fraction at every amplitude (38% left at 1 R, 6% at 10 R), pure diffusion, untouched by the ring's dynamics. In water the seed survives: 0.39-0.40 of the launch spin remains after nine radii at every amplitude, the levels stay separated (a quarter-swirl ring arrives with 4.6 mm/s of spin, half 9.3, full 19), the sign is held, and the price list is a quarter swirl for 0.7% of speed and 0.8% of distance, half for 2-3%, full for 8-11%. The caveat is structural and stated: the grid is axisymmetric, so only the axisymmetric burst is excluded; the three-dimensional bending modes are not hosted. The design point is to sign the rings lightly — two or three amplitude levels are readable at a station-keeper's distances, a couple of bits per ring — and the verdict is that the data channel exists and is priced, while swirl as a power channel is a loss.

Rung 5a — the stroke alone is a pump. The body was freed: its axial velocity follows from the force the fluid puts on it, the force of record being minus the change of the fluid's hydrodynamic impulse across the penalization step (transport conserves it; only the body changes it), with an added-mass stabiliser of 0.60 kg stated as a stabiliser and not as physics, first-order in time. Three failures on the way are recorded: a quasi-static flap slewed at 30 rad/s; a stabiliser sized for a bare hemisphere diverged because the bell drags its cavity and its outer added mass; and the body force taken from the raw correction had the wrong sign, then the wrong size, until it was written as the impulse change. With a rigid rim and the symmetric radial stroke through an open mouth, the bell settles into a repeating cycle by the second stroke — -24 mm/s at peak contraction, +21 at peak refill, identical every cycle — and nets +0.06 R per cycle mouth-first, three millimetres backward per stroke, at Reynolds 300 and +0.04 to +0.07 in water. The starting ring never departs, because there is no

mean body velocity to leave it behind, and the parked stopping vortex accumulates cycle on cycle. In water the starting rings stack and the stack drifts away down the jet while the parked vortex grows toward the mouth plane: momentum goes into the wake in both signs, bound together under and behind a bell that cannot leave them. That pair, at two viscosities, is the cleanest possible baseline — a stroke that goes nowhere — and every design element after it is measured as a difference from it. The fully passive flap, coupled through either of two estimates of the moment a global correction puts on a fifteen-millimetre tongue, is unstable and is set aside as its own piece: the next case prescribes the margin.

Rung 6 — the animal's stroke swims, and the engine is at the rim. The free body of rung 5a was given three parts read from the author's frames (§7D), each switchable: a shape change, the bell deepening as it narrows (oblate to prolate, $H = H_0(1 + 0.4 x)$); a folding lip, a 0.3 R lappet that swings 45° inward at full fold and shuts the annular slot to 0.09 R; and a central plug of 0.5 R, the oral arms. With all three on (author's laptop, 11 September, Reynolds 300, 1 mm, four cycles) the bell swims apex-first, $-0.115, -0.217, -0.204, -0.189$ R per cycle, settling near a fifth of a diameter per cycle where the rigid bell crept the other way; peak contraction -24 mm/s, the refill's pull-back $+5$ mm/s falling to nothing by the third cycle. A real Aurelia does somewhat better, a few tenths of a diameter per cycle at abstract level, and the first-order coupling and screen-read kinematics are the obvious reasons; the sign and the order of magnitude are the animal's. The three switch-off runs price the parts. Without the lip the bell barely moves, -0.015 to -0.019 R per cycle: the fold and its closure are almost the whole thrust. Without the plug — which is the moon jelly as built — a fifth remains, -0.03 to -0.05 . Without the deepening, $-0.07, -0.16, -0.23, -0.17$: the prolate shape is worth nothing or slightly less than nothing, a side effect of the fold rather than a cause of thrust. The engine is the rim: a lip closing an annular slot over a plugged centre. One wrong run is kept for what it says: a build in which the pinch argument scaled the lip and the deepening but was never passed to the stroke produced a no-plug bell with a half-strength fold, and it rocked like the pump — halve the fold and the swimmer stops.

The moon jelly, the pinch and the slow return. The moon jelly has no plug; the author's reading of his own frames (§7D) is that it makes up for it by pinching a small chamber hard, expelling most of it through a rim that closes, and that its dome is the spring that powers the whole return. With the pinch (rim contraction 0.45, about seventy percent of the chamber expelled, no plug) the bell starts faster than any case — -57 to -64 mm/s, -0.30 R apex-first by 0.4 T every cycle — and the open-mouth refill then hauls it back at $+50$ mm/s to a net of $+0.03$ R per cycle the wrong way. Two things in that run are real: the starting rings now depart cleanly and stack nearly three radii behind the mouth by the fourth cycle, which the twenty-percent stroke never did without the plug; and the refill is a second jet the other way, seventy percent of the chamber back through a wide rim in 0.6 s, shed off the exumbrellar side behind the bell. The animal does not inhale as hard as it exhales, so the next knob was the relaxation's duration: the contraction pinned at 0.4 s and the return stretched to 1.6 s. The two-millimetre proof of that case, one cycle, was half right. The refill's peak speed fell from $+50$ to $+15$ mm/s, the direction predicted, and the second jet weakened; but the body still came back, to $+0.065$ R against $+0.125$ for the fast return at the same resolution — the knob halves the creep and does not change its sign. The reason is a theorem's cousin: in an ideal fluid a body that swallows a fixed volume moves back a fixed distance however slowly it swallows it, so slowing the refill cannot by itself make a swimmer, and only vorticity kept under the rim or left behind can break the symmetry. The one-millimetre three-cycle run (author's laptop, 12 September, 74 min measured against 80 derived) overturned the coarse proof's sign: $-0.051, -0.055, -0.047$ R per cycle apex-first, steady from the first cycle, where the fast return at the same resolution gave $+0.068, +0.026, +0.029, +0.025$ the other way. The pinched moon jelly with a slow spring return swims. The refill's peak pull-back is $+12.7$ mm/s against $+50$; the starting rings depart cleanly to four radii behind the mouth; the negative-sign wake behind the bell is half the fast case's (-31 against -62×10^{-3}) and its centroid drifts steadily away at close to a radius per cycle instead of parking. The disagreement is printed: the two-millimetre one-cycle proof read $+0.065$ R and the one-millimetre run reads -0.051 — the coarse grid could not hold the vorticity under the rim that breaks the swallow-and-return symmetry, which is exactly the mechanism the ideal-fluid argument said had to do the work, and at the finer grid it does it. So the coarse proof is retired as a sign indicator for this case. The half-millimetre check (author's laptop, 9.3 hours measured on a machine sharing five runs) confirms the sign and moves the magnitude: -0.119 and -0.134 R per cycle against -0.051 and -0.055 at one millimetre, with the refill's pull-back at $+11$ mm/s. The resolution walk for this case now reads $+0.065, -0.051, -0.119$ at 2, 1 and 0.5 mm, and it has not converged: the swimming grows as the rim's vorticity is resolved. The disagreement is printed, and its consequence is stated: every one-millimetre swimming number in this file is a lower bound on the trend it reports, the sign and the ordering of cases are the results, and the magnitudes carry the half-millimetre tag until each case has its own check. Per unit time the moon jelly is slow: -0.026 R per second against the nettle stroke's -0.2 R per one-second cycle, a quarter of the distance per cycle and an eighth of the speed. That is the trade the animal's two anatomies make explicit — the plug buys speed, the spring buys a swimmer that needs no plug — and the cavity profile, a bowl with a lip rather than an ellipse, is the knob after it.

The slower return, and the pace pair at ten times the viscosity. Stretching the return again — contraction still 0.4 s, return 3.6 s, a four-second period — the same bell goes $-0.232, -0.250, -0.300$ R per cycle, growing, with the refill's pull-back down to $+3.5$ mm/s: the body surges to -0.30 R and then essentially stays there while the spring reopens the bell. That is five times the distance per cycle of the 1.6 s return and, even on the longer period, nearly three times its speed, -0.06 to -0.075 R per second against -0.026 ; per cycle it now matches the sea nettle's plugged stroke (-0.2 R) on a bell with no plug at all. The starting rings depart to more than five radii, and the run time was 2.5 hours measured. A still longer return, 7.6 s on an eight-second period, gives $-0.52, -0.48$ and -0.54 R per cycle — twice the four-second return's distance — at the same -0.065 R per second: the curve bends exactly where the animal's own ratio sits. The rows say why. After the 0.4 s surge to -0.31 R the body's speed decays to nothing by about four seconds and then holds; the extra return adds no distance, only waiting. Four seconds is the water's forgetting time for this bell measured directly — the coast after the push — and the animal's one-to-four is the return that uses all of it and none more. Per second, the plugless moon jelly's ceiling on this axis is about -0.07 R per second, a third of the nettle's plugged stroke. The same loop was then walked at ten times the tank viscosity (Reynolds number near 30, boundary layer a centimetre, fully resolved): the fast return there goes $+0.12$ R per cycle mouth-first and the slow return $+0.055$, same sign, less than half the size, with the rings never leaving the bell — a viscous pump at both paces. The reading is that distance per cycle already depends on the pace of the loop at Reynolds 30, so that regime is not the memoryless one of the low-Reynolds theory, but the sign of the answer is pace-independent there and flips only by Reynolds 300. The slow return at Reynolds 100 sits on the flip itself — $+0.012, -0.009, -0.026$ R per cycle, drifting through zero — so the bifurcation for the animal's return lies near Reynolds 100 at one millimetre, and the fast return there still pumps at $+0.09$. Across the rungs the slow return reads $-0.04, +0.055, 0, -0.05$ at Reynolds 3, 30, 100 and 300: not one crossing but two, the honey-side one being the small inertial residual of a scallop and the water-side one the memory switching on. A stronger version of the test, the same loop walked backwards in time — the mirror stroke, 1.6 s in and 0.4 s out on the same 2 s period, for which a memoryless swimmer must return exactly the negative of the forward distance — was run at both viscosities (§13): at Reynolds 30 the reversed loop goes the same way as the forward one, $+0.02$ to $+0.09$ R per cycle, so reversing the loop reverses nothing and the sum of the two, about $+0.07$ R per cycle, is the fluid's memory measured in the loop's own units; at Reynolds 300 the reversed loop pumps once from rest, $+0.135$ R, and then swims at $-0.58, -0.65, -0.63, -0.65$ and -0.62 R per cycle over six cycles — a periodic steady state from the second cycle on, the body's speed profile repeating to the millimetre per second (-39 mm/s at peak push, $+69$ at the snap-open), the wake's circulations saturating rather than growing. It is not a coupling artefact; a first-order coupling cannot manufacture a bounded limit cycle. It is the fastest swimmer in this file, -0.31 R per second, half again the sea nettle's plugged stroke, and it is the opposite of the animal's timing — slow squeeze, fast snap-open — which a spring-only return cannot produce. Its half-millimetre check is the remaining tag, and by §13's rule the one-millimetre value is a lower bound.

The frequency axis. The duty sweep changed the return alone. Scaling the whole cycle at the animal's 40/60 — periods of 0.5, 1 and 2 s — gives $+0.02, +0.03$ and $+0.06$ R per cycle mouth-first in the settled cycles, which is about $+0.03$ R per second at all three: the bell drifts at a speed the fluid sets, not a distance the stroke count sets, and the sign does not move across a factor of four in frequency. At the fastest period the wake's circulations are six times the one-second case's; the bell is churning, not swimming. So the two axes are different objects: the return's duration relative to the fluid's forgetting time decides whether the bell swims, while the whole-cycle frequency at fixed shape decides only how hard it churns. Three points at one millimetre, lower bounds by §13's rule.

The leash — thrust at zero speed. A free swimmer is force-free over a period by definition, so the free runs above never measured thrust; they measured the speed at which thrust balanced drag. Holding the bell at zero speed and integrating the fluid's force on it gives the station-keeper's number directly, and it reorders the results. The animal's 40/60 rocker, which pumps backward when free, delivers a steady -86 mN·s per cycle on a leash — an 85 mN mean thrust apex-ward — with the return contributing nothing. The slow stroke held still delivers the same push, -86 to -89 mN·s, and its return adds -8 : the contraction's impulse on a leash is invariant, set by the pinch and the lip's cut and indifferent to what follows, and the return is worth about nine percent with the animal's timing — passive recapture measured on a still bell. Per second, then, the leash favours frequent strokes 3.6 to 1, the opposite of the free swimmer, which is reconciled by one fact: the free swimmer's slow-return advantage was entirely the avoided haul-back, a moving-body penalty, never extra thrust. The snap-open stroke, the fastest free swimmer in this file, delivers only 35 mN on a leash — its speed was a running start, the mirror image of the same penalty. Station-keeping wants the animal's fast contraction; cruise wants the snap-open. The leash's thrust turns out to be the most robust number in this file. At half a millimetre the rocker delivers -88 and -90 mN·s against -86 at one millimetre — converged, the one family so far that needs no direction-of-correction tag — and across the fluid it barely moves: -71 at Reynolds 30 (with a $+15$ pull-back in the return), -94 at 100, -86 at 300, and -95 in water at the animal's own viscosity. The contraction's impulse is a property of the stroke — the pinch and the lip's cut — to within fifteen percent over two decades of viscosity. Recapture saturates: the return adds -8 mN·s whether it lasts 3.6 or 7.6 s, nine percent either way, which is what the parked ring's four-to-five-second life predicts — by the time a longer return could collect more, there is nothing left.

The push's duration. Holding the animal's 3.6 s return and varying the contraction alone gives the strongest single knob in this file: a 0.8 s push swims -0.06 R per cycle, the animal's 0.4 s push -0.25 , a 0.3 s push -0.44 , a 0.2 s push -0.66 , and a 0.15 s push -0.77 — the last at -0.21 R per second, three times the animal's timing, from the same bell with no plug and no valve. Taken pairwise the axis is not one power law: two inverse-square steps and then exponents of 1.0 and 0.5 — it saturates, which a four-point fit had hidden (a companion analysis caught it, and a decision rule written before the 0.15 s run confirmed it). The reading that fits is a product: the impulse launched, which goes as one over the push time, times the haul-back avoided, which improves with push speed until there is none left to avoid. At half a millimetre the 0.2 s push swims -0.86 and -0.84 R per cycle, -0.22 R per second, 1.3 times the one-millimetre value and steady across both cycles: the family's correction is upward, as the animal's was, and smaller, because a stronger ring is better resolved on the coarser grid. The rim's peak speed sets the starting ring's circulation, and the ring's circulation sets everything after. So the stroke's two halves read in two clauses: the contraction's duration is the ring's strength, the return's duration is the refill's mercy, and the animal sits at the fast end of one and the slow end of the other. The return sweep is complete at 0.6, 1.6, 2.4, 3.6, 5.0 and 7.6 s — speed rises to about -0.07 R per second by 3.6 s and holds there through 7.6 — so the plateau begins at the forgetting time. The fast push has its own return curve: -0.13 R per second at a 1.6 s return, -0.18 at 2.4 and 3.6, -0.14 at 5.0, so its knee lies between 1.6 and 2.4 s, a second earlier than the animal push's — a harder push needs less mercy from the return.

Launch-and-lean. The reversed timing — a slow 0.8 s squeeze and a fast snap-open — does something on a leash that no free run showed. The first cycle delivers almost nothing, -37 to -42 mN·s, because there is no wall yet. From the second cycle on, each contraction begins against the vortex the snap parked a fraction of a second earlier, with a spike of force at the cycle boundary, and the impulse per cycle rises as the snap shortens: -76 mN·s at a 0.4 s snap, -104 at 0.3, -168 at 0.2, -350 at 0.1 — roughly inverse to the snap's duration, the same law the push follows, so the lean is the push's echo. At half a millimetre the 0.1 s case reads -428 , a fifth above the one-millimetre value: the wall is vorticity the coarser grid under-resolves, and a held bell has no body-coupling correction, so this family corrects upward where the free snap swimmers corrected down. At matched duration the lean is the push's equal within the tool's precision. Per second it is the largest station-keeping thrust in this file, 476 mN at a 0.9 s period, and it belongs to a machine: a 0.1 s reopening is an actuator's motion. The peak forces sit on rows where the mask changes within a step and are reported as trends; the impulses are the numbers.

The comb that was not there. A companion analysis predicted structure in the leash's impulse at simple ratios of stroke period to the parked ring's lifetime, and named what would kill it. Seven periods from 1 to 8 s, ratios 0.2 to 1.8 of the ring's four-to-five-second life, held at zero speed: -85 , -97 , -99 , -98 , -96.5 , -95.6 and -95 mN·s per settled cycle, flat within three percent once the return exceeds a second. No tooth; the mapping is dropped on the null. What the test bought is worth more than a tooth: a free swimmer at steady state is a closed loop in its own frame — shape, velocity and body-frame wake all return, only position does not, and position is a gauge — so the distance per cycle is that loop's holonomy, and the genuinely open case is a stroke whose timing jitters, not a bell that moves. A comb needs countable units arranged in a cycle; a line of identical bells swimming in file would have them, and is the next instrument.

The one-way valve. An intake at the apex — open wherever the local flow enters the cavity, solid against outflow, the squid's funnel valve as a mask — was the lever the leash ranking put first. On the leash it adds 8 to 17 percent by turning the return apex-ward. On the free swimmer with the animal's timing it more than doubles the distance per cycle, -0.57 , -0.65 , -0.57 R against -0.25 , because the refill entering from behind carries the bell forward through the return and the coast disappears. Two things travel with that number. It is the machine's row, not the animal's, which has no valve and cruises. And the valve as modelled is unstable: re-decided cell by cell every step, it chatters, and in three of six runs — a held bell, and free runs with a 0.2 R cap — the chatter grew until the solver failed. The three that finished carry that tag until a valve with hysteresis and a finite opening time, which real valves have, replaces it. The doubling is reported as what an ideal valve did in the runs that survived.

The phase cliff. The phase between rim and lip, swept finely on the animal's swimmer, is not a hill with a peak but a plateau ending at a cliff: a lip folding 0.12 s before the rim stops swims as well as the exact lock or a hair better, 0.24 s early halves the swim, and 0.12 s late turns the swimmer into a pump, 0.24 s late into a strong one. The mechanism is whether the ring gets cut — a late lip leaves the slot open when the rim stops and the refill begins into a bell that never sealed. So the work maximum on the shape's phase axis is at the lock, and the pace that pays lives in the fluid's phase, the return's duration. Read as a driven oscillator, the work curve's refusal to peak at quadrature is the store announcing itself. The measure of that store is the power factor of the stroke — the real power the bell exports over the apparent power it exchanges, rms force times rms velocity — with the reactive fraction $\sqrt{1 - PF^2}$ as the share that sloshes; both are bounded, both are accumulated inside the tool every step. At one millimetre the free 40/60 bell runs at a power factor of -0.083 (reactive fraction 0.9965): about 0.4 mW of real power against 4 to 5 mW apparent. Ninety-nine percent of what the bell does to the water comes straight back. The fluid is a spring and the stroke's whole job is the residue. The same column on the leash reads $+0.80$ to $+0.86$ for the actuator pair across Re 30 to water — and the parked stopping vortex, whose radius breathes 0.43 to 0.62 R with the bell at held circulation, lagging the rim by a tenth of a period and following it at less than half its swing, is the spring's visible part.

The tools of record, and their check. Every rung is a script with a double-click batch file whose case is baked in, and every laptop run is a time-stamped run file deposited with this paper; run times are measured in the container and scaled, or stated as derived with the derivation. A standing fidelity check reruns rungs 1, 2, 3 and 6 against their run files of record after any tool change and prints pass or fail per number at five percent; its first run caught a stale copy of the rung-3 script that had been shipped in place of the version of record, and its rung-6 leg reproduces the four-cycle verdict run's first cycle to every printed digit.

7A.x Three further stages

The valve that holds its breath. A one-way cap at the apex that opens on the sign of the local inflow chatters: three of eight runs blew up. The same cap given hysteresis — it opens above five percent of the rim's peak speed and closes below minus five, over a four-step ramp — runs the free 40/60 rocker for six cycles at a millimetre without an abort, and the rocker does something the sign-rule valve never did: it hovers. Its displacements are -0.021 , -0.089 , -0.026 , $+0.039$, -0.009 and $+0.045$ radii per cycle, a mean of one hundredth of a radius, the sign changing from the fourth cycle on. On the leash the same valve adds nine percent to the mean pull, steadies the push half of the stroke and leaves the return half swinging, so it is not a steadier valve, it is a differently timed one. On the slow-return stroke it fails: after one cycle of -0.686 R the body runs away, and the sign-rule valve of record did not. That failure is banked with its number and its suspects — the ramp opening the cap into a resting cavity while the body is free to go with it — and is not closed until the ramp has been priced.

The stroke must land on its own wake. The clock-locked 40/60 swimmer moves $+0.076$, $+0.031$ and $+0.024$ R in three cycles. Given a rest of a tenth of a period before the second stroke and a fifth before the third, the same swimmer moves $+0.076$, -0.002 and -0.081 : the first cycle identical to the digit, because the first pause comes after it, and the next two changed by their own size and then reversed. Nothing in the stroke changed; only the phase at which it met the vortex it had parked. This is the cheapest run in the paper and it reads the per-cycle numbers of every 40/60 case for what they are: a measurement of the wake's phase at launch, not of propulsion. It is also the open-loop test the comb of return periods needed and did not have — a comb that dies under a tenth of a period of jitter was never a comb.

The push axis at a short return. A 0.15 s contraction with a 1.0 s return moves -0.19 R per cycle, -0.17 R per second; the same push with a 3.6 s return moves -0.78 R per cycle, -0.21 R per second. Per second the short return keeps four fifths of the long one's speed at a third of the period. The knee of the return curve lies between 1.0 and 3.6 s. And the fast push is the only stroke in this paper whose start ring stays a thin ring through three cycles; the rocker's start vortex is a sheet from the moment the lip folds.

The phase test, run. Section 9's eleventh test asked for the second cycle's displacement against a rest inserted before its stroke. Five points now: $+0.031$ R with no rest, then -0.002 , -0.036 , -0.075 and -0.123 R at rests of 0.102, 0.205, 0.307 and 0.409 T, the first cycle $+0.076$ R in every run to the digit. Monotone, and a straight line to the eye — about -0.37 R per period of rest — crossing zero near 0.095 T, before the 0.15 T the prediction required. The memory reading stands. The straightness is the thing to keep: the stroke's displacement falls linearly with the delay, which reads as the parked vortex fading at a steady rate through the window the stroke can land in, not as a resonance.

The two clocks on the leash. The tethered slow-return stroke at Re 30, 100, 300 and water: the body forgetting time as the leash measures it (the last crossing of five percent of the cycle's peak force) is 0.41, 0.41, 0.52 and about 0.50 s — a quarter of movement across a hundredfold in viscosity. The stop vortex's circulation lifetime, fitted on the tracked window, is 3.7 s, 7 to 8 s, at least 15 s, and longer than the window at water. A constant ratio of the two, the prediction under test, needed a spread under fifteen percent; the spread is a factor of two between the clean rungs and at least three to Re 300. On the leash the water's memory of the ring grows with Reynolds number roughly as diffusion says and the leash's memory of the push does not grow with it. The two clocks are not one. This is a fact about the tethered body; the free body's forgetting time is a different quantity and has not been measured across the rungs. The leash also carries a flat residual pull of about -4.7 mN through every return at every viscosity, so its one-percent crossing never resolves.

The valve on the slow return, salvaged and read. The breath-holding cap that hovers on the 1 s stroke runs away on the 4 s one: with a four-step opening ramp the free body aborts at 1.044 T; with sixteen steps at 0.942 T; with sixty-four steps it runs all three cycles, -0.340 , -1.207 and -0.204 R, the sign-rule valve's mean pace with a sixfold spread. The spread is three machines, not noise. The mass-balance column — the mouth's inflow over the cavity's volume change, hence the mouth's share of the refill once an apex valve is open — reads the three apart. In the first cycle the refill enters mostly through the apex, the mouth's suction that would pull the bell apex-ward is gone, and the body parks: the hover on a slow stroke. In the second the mouth's share falls to zero and then negative while the plus circulation in the wake triples: water in at the apex and out at the mouth for the whole return, a through-flow duct, a jet, and a feedback loop with the right sign to run away — the faster the body moves apex-first, the more the cap stays open. The ramp decides whether that loop diverges or saturates. In the third the body has stopped moving apex-first, the cap shuts, the refill comes through the mouth against the enormous wake of the second cycle, and the bell is pulled back. On the leash, where the body's speed is zero by construction, the same valve runs -94.4 , -93.8 , -94.0 mN s, steady to half a percent, against -93.9 to -96.5 for the stroke with no valve: it moves the refill from mouth to apex and leaves the impulse alone. The duct mode is a machine the animal does not have, since an animal's bell has no apex hole, and it is the first stroke in this program to make a start ring during the return.

7B. The fork: pump and swimmer are two designs

The rigid-margin cap that pushes and pulls through one aperture is a poor swimmer and a legitimate oscillating pump. Everything it does well — starting-ring formation, the station-keeping ring of the acoustic radome (§7), the Cassiopea posture that ventilates a habitat (§8), array leapfrog, the acoustic budget (§6) — the inviscid tool now prices honestly, with mass balance verified at every stage. That is the station-keeping research platform, and the tube-and-torus engine of §4 drives it as drawn.

The swimmer is different. Its propulsor is the margin: the flap bends inward on contraction and flicks outward on relaxation, and half the thrust arrives in relaxation. Two resonances are documented in the animal, and they are different things. For forward swimming the bell is driven at its frequency of free vibration (Demont & Gosline; Hoover & Miller 2015; Hoover et al. 2019 — the A1 prior art). For turning, Hoover et al. 2021 (read in full) show a second resonance: the muscular activation wave travels CIRCUMFERENTIALLY around the margin from one pacemaker, and when its speed matches the mesoglea's elastic wave speed $\sqrt{E/p}$ — 0.32 m/s at 100 Pa, against a measured 0.47 ± 0.13 m/s in Aurelia — the margin hyperextends on the far side, the stopping-vortex ring becomes asymmetric (34-fold in circulation) and the bell turns, 76-fold better than off-resonance. That is the travelling rim mode of §5 as the animal does it, and it fixes a number the OAM channel lacked: the mode's phase speed is pinned to $\sqrt{E/p}$. No apex-to-margin travelling wave is demonstrated in these papers; the zipper rail of §4 — a travelling squeeze crown to rim — is therefore a design idea with a squid-mantle analogy behind it, not prior art. It remains the program's only mechanism that turns the engine's stroke into margin motion with a phase lag, and it is promoted to the swimmer's candidate load-bearing element on that ground; its natural embodiment is a ribbed umbrella driven in sequence from the crown with an independent iris at the tips. What the animal's stopping vortex is documented to do, across the papers now held: act as the wall the next stroke pushes against (Gemmell 2021), direct the refill into the cavity at no metabolic cost (Gemmell 2013; Hoover 2021), pair with the starting ring into a jet (Neil & Askew), and, made asymmetric, pull the bell through a turn by subumbrellar suction (Hoover 2021). Four documented jobs for one vortex; sensing and prey capture are not among them in these sources and stay open. The slug and torus are not discarded; they drive the ribs rather than the skin. Two actuator channels, the stroke and the margin. A swimmer's efficiency is mostly recapture, so its pricing waits on the viscous build; every design decision that does not ride on recapture can be made now. The falsification point for any swimmer design: a machine that only pushes gets at most the contraction half of the animal's thrust budget and none of its recapture. And the swimmer's second channel need not be an actuator: Villanueva's passive flap and stage 7's spring hinge say a tuned tapered tail at the margin gets its timing from the fluid and its swing from its stiffness, which is a simpler machine than the two-channel one argued above — the slug and torus drive the stroke, the water times the tail.

The fork now has a third time, and it is the one the whole program was reengineered toward. The pump is the rigid cap. The swimmer is the margin with recapture. The hoverer is the swimmer with the breath-holding valve, timed so that each stroke lands on the parked vortex at the phase that cancels the last: six cycles, no net motion, no abort, the water doing the station-keeping. Its falsification point is the same as the swimmer's — a machine that only pushes gets the contraction half of the budget and none of the recapture — with one line added: a machine that cannot choose the phase of its stroke against its own wake cannot hover, because a tenth of a period decides the sign.

7C. The ring as a signature

The ring is the product, and it deserves a section of its own. A thin-core ring is three numbers and a shape — circulation, ring radius, core radius, and the distribution of vorticity across the core — from which the impulse $\rho n \Gamma R^2$, the energy $\frac{1}{2} \rho \Gamma^2 R [\ln(8R/a) - 7/4]$ and the self-induced speed $\Gamma/(4\pi R) [\ln(8R/a) - 0.558]$ follow (Saffman). A fourth number is swirl, an axial flow along the core; a fifth family is the bending waves on the core, which give the ring a mode number and, at the wavelength of the core size, the Widnall instability that ends its inviscid life. The author's image of the ring as an inverted rubber band is literal: a filament under its own induction moves like an elastic string with tension proportional to Γ^2 times a logarithm, and its bending waves are Kelvin waves. For a closed vortex tube the helicity — the conserved topological quantity of the flow — is $\Gamma^2(Wr + Tw)$, writhe of the centreline plus twist of the core (Moffatt & Ricca 1992, the Călugăreanu-White formula for vorticity); the sum is conserved inviscidly while the partition can move, and that partition is the writhe reader of the topology program applied to a wake, with a conservation law beneath it. The amplitude a single stroke can put into one ring is clipped by Gharib's formation number near a stroke ratio of four; above it a trailing jet pinches off instead.

The signature is not where it was looked for. The start ring that leaves the mouth is a thin ring only through the first three tenths of the first cycle; from the moment the lip folds its core outgrows its ring radius and it is a spreading sheet with a shear layer, and the circulation that the whole-wake column reported was, after that moment, mostly circulation piling up outside any ring's neighbourhood. The object that stays a ring is the stop vortex parked under the rim. It loosens during each contraction and tightens in each return, and the energy in its tight core grows cycle over cycle — nineteen, twenty-five, forty-one millijoules at two millimetres, its core pressure deepening to minus 373 pascals — while its centroid does not move: at water viscosity it sits at 0.55 R from the axis for two full cycles. That is the parked ring, the one W0 named as a pathology and the recapture share named as an asset, and any signature of this swimmer is read there — with one viscosity caveat. On the slow-return stroke at Re 30, 100 and 300 the stop vortex sits under the rim for the whole run, its centroid within 0.4–0.7 R of the axis and a third of a radius of the mouth. At water viscosity it does not: at 0.6 T of the first cycle its centroid jumps from under the rim to two radii out and downstream and stays out for three cycles. The recapture object is parked at Re 300 and below and shed at water viscosity on this stroke, so every water row in the ledgers is read as a shed ring, not a parked one.

The stopping vortex now has five documented jobs across the papers held: the wall the next stroke pushes against (Gemmell 2021), the refill director (Gemmell 2013, Hoover 2021), the partner in the thrust-carrying pair (Neil & Askew 2018), the asymmetric turning pull (Hoover 2021), and — from Costello & Colin 1994 — the feeding apparatus: the swimming flow entrains prey slower than the margin and carries them to the tentacles, while prey that can out-swim the margin escape. Pairing also makes the wake quiet, since the low-frequency sound of vorticity goes with time derivatives of the impulse and a paired structure with steady total impulse radiates far less than a lone accelerated ring; that quietness is a consequence of the pairing, and whether it is also a purpose is not established in any source held.

Appendix C — Threads not pursued here, and where each would start

The Tesla valve as the two-stroke's valve. Pursuable. A Tesla valve is a leak whose size depends on the flow direction; the tool's valve already has a leak knob, so the first run is a direction-dependent leak fraction (one print-only knob, v2.4) on the 40/60 hover and on the slow return, priced against the null: does a diodicity of 2 to 10 degrade the hover's mean by that ratio, as §10 predicts? Artifact: two 1 mm runs and the ledger.

The iris. Pursuable in axisymmetry. A pinwheel cannot be drawn in this solver, but an iris is a radius schedule at the mouth, and the formation-number argument of §11 ($FN = A L^2 / D^3$) only needs the radius. First run: the 40/60 stroke with the mouth radius closing to 0.7 R through the contraction, read for the start ring's circulation and pinch-off time against the fixed-mouth record. Artifact: one 1 mm run and the ring columns.

Ring leapfrog in a staged array. Pursuable and already numbered: a half-strength same-sign follower inside the margin gave a 31 percent ring-speed gain. Next: the spacing sweep, three runs at 1 mm on the existing ring tool. Artifact: the sweep and its curve.

The chords through vortex waveguides and the Arnold-tongued chords. held by the author until a definition exists; they are not untested, they are undefined, and the paper says exactly that in one sentence.

The tesseract as a closed loop in a state space with more dimensions than any projection shows. Kept as framing in §0A's language; it is a way of seeing, and

the author’s definition of the design that grew from it: the dual-tesseract chaser drive is the multi-bell lead-lag drive in which $n \geq 2$ bells operate in phase sync and produce a Tower-of-Hanoi latched quadrature drive. It is not built or tested in this paper.

The second-skin suit is priced elsewhere in this paper (K2).

Appendix D — Provenance

number	source	tag
Aurelia 0.10 m, 1 Hz, 0.02 m, 0.06 m/s; St 0.33 document, recomputed		UNVERIFIED inputs, arithmetic SOURCED
48%, 30%, Froude 0.09–0.53 / 0.8	Gemmell et al. 2013 PNAS	SOURCED (abstract + text)
1 BL/s, 10–50×	Bujard et al. 2021	SOURCED (abstract + press)
Chen 2022 (D/d, L = 3.6); New 2024 (Re 3000, shear peak); Dora 2009 (M 1.35–1.76)	supplied by author	SOURCED (abstract / partial full text)
plate λ^2 9.08; drumhead 2.405; β 0.65; strain limits; E mesoglea 1 kPa	jelly_hL_scan.py	SOURCED / UNVERIFIED / ASSUMED as marked in file
1.2 m/s at h/L 0.1 or 3 cm skin; FN wall 0.3; U_{recap} 0.84	jelly_hL_scan.py, jelly_self_timing.py	model output
262 kg, 41 kN/m, 400 N, 800 W, 5%; Q_{min} 102	jelly_slug_engine.py, jelly_spring_q.py	ASSUMED model
23 N·m, 3 s; 38 kW, 48/380 daughters; 0.74 kWh/m ³	jelly_oam_torque.py, jelly_matriarch_budget.py	ASSUMED model / SOURCED
179 dB, 7 W; –38 dB pair; –18 dB at 10 m	jelly_acoustic_null.py	wave theory SOURCED formulae, ASSUMED full volume pulse, free field
microseism floor shape; ~95 / ~130 dB levels; 160 km / 2 km / 28 km / 350 m	NRC 2003, Wenz 1962 (search); jelly_pair_cancel.py; recomputed	shape SOURCED, levels
1.3% / 0.7°; 41 ppm at Q 150; 74° at 3% mismatch; –44 dB two-stroke dipole	jelly_pair_cancel.py, jelly_pair_sensitivity.py	ASSUMED SOURCED formulae
$\beta = 0.85$ (Lamb disc)	analytic	SOURCED (upper bound)
Stokes floor –0.085 R/cycle vs 0.010 bar (FAIL)	run_..._stokes_kat_4mm_1cyc_20260916_2258 (laptop) = container proof 0.0848	model output, tool v2.0
hysteresis valve, free 40/60: –0.021/–0.089/–0.026/+0.039/–0.009/+0.045	run_..._free_duty04_valve03_hyst_6cyc_20260916_2350	model output, 1 mm
R, mean –0.010, no abort		
hysteresis valve, leash: –91.7/–85.1/–106.5 mN s vs sign rule –86.4/–100.9/–92.2 vs none	run_..._tether_duty04_valve03_hyst_3cyc_20260916_2258; 13 Sep 1212 records	model output, 1 mm
–85.9/–86.1/–84.8		
hysteresis valve, slow return: –0.686 R then ABORT 1.044 T	run_..._free_duty01_valve03_hyst_3cyc_20260916_2350	banked negative
jitter: +0.076/–0.002/–0.081 vs clock-locked +0.076/+0.031/+0.024 (pauses 0.102 T, 0.190 T)	run_..._jitter02_duty04_3cyc_20260916_2258 vs run_..._pinch_defaultpath_3cyc_20260914_0842	model output, 1 mm
push 0.15 s / 1.0 s return: –0.192/–0.201/–0.170 R (–0.17 R/s) vs 3.6 s return –0.78 R (–0.21 R/s)	run_..._contraction_015s_return10s_3cyc_20260916_2258; 14 Sep 1447 record	model output, 1 mm
Re 30 leash on v2.0 = record to the digit (–58.609/–70.585/–71.242)	run_..._tether_re30_duty04_v20_3cyc_20260916_2258 vs 13 Sep 2155	fidelity, 1 mm
water leash 1 mm –90.1/–91.7 vs 0.5 mm –96.5/–93.9; stop vortex parked at $r \approx 0.55$ R	run_..._tether_duty04_water_1mm_2cyc_20260916_2258; 13 Sep 2155	model output
two cycles		
plus ring thin only to 0.3 T; stop vortex re-tightens each return (E– 19–25–41 mJ, –373 Pa at 2 mm); tracked box holds 37–44% of G+, 52–70% of G–	six container proofs (v2.0 tool) and the ring-columns pass, deposited with this paper	trend, 2–4 mm; the earlier wake-G+ rows above read as cloud + shear after 0.4 T
power factor, free 40/60 at 4 mm: PF body –0.27/–0.33 (reactive 0.96/0.94); leash PF_act v2.2 container proofs 17 Sep +0.60		trend, 4 mm
power factor, free 40/60 at 1 mm: PF body –0.083 (reactive 0.9965), $P \approx 0.4$ mW, $S \approx 4$ –5 mW; leash PF_act +0.80/+0.83/+0.85/+0.86 (Re 30→water)	run_...v23_phase_pause0204/0306/0408_duty04_2cyc_20260918_0012; run_...v23_f3_tether_duty01{re30,re100,re300,water}_3cyc_20260917_1544	model output, 1 mm
phase test: second cycle +0.031 / –0.002 / –0.036 / –0.075 / –0.123 R at rests 0 / 0.102 / 0.205 / 0.307 / 0.409 T		model output, 1 mm; PASSED
leash coast 0.41 / 0.41 / 0.52 / 0.50–0.53 s; $\tau_{\text{au}} = 3.7 / 7\text{--}8 / \geq 15 / >\text{window s}$ (Re 30 →	run_...v23_f3_tether_duty01*_3cyc_20260917_1544	model output, 1 mm; ratio

water)		not constant
leash residual -4.65...-4.89 mN through every return, all four rungs	same four files	fence
leash impulse on the slow stroke -76.4 / -90.5 / -96.5 / -96.4 mN s; with hysteresis valve at Re 300 -94.4 / -93.8 / -94.0	same four files; run_..._v23_tether_duty01_valve03_hyst_3cyc_20260918_0012	model output, 1 mm
hysteresis valve, slow return, free: ramp 4 ABORT 1.044 T; ramp 16 ABORT 0.942 T; ramp 64 -0.340 / -1.207 / -0.204 R	2350 (16 Sep); ramp16 2229; ramp64 2229	salvaged as mechanism, fenced as design
mouth's share of refill (mass-balance column) in the ramp-64 return: cycle 1 0.50...0.08; cycle 2 0.32 → -2.67; cycle 3 0.85...1.0	run_..._ramp64_3cyc_20260917_2229	model output, 1 mm
stop vortex at water on the slow stroke: centroid jumps from (0.44, -0.14) R to (1.09, +0.96) R at 0.6 T and travels to ~2 R out	run_..._f3_tether_duty01_water_3cyc (1031 and 1544)	model output, 1 mm; both tool versions
end-of-contraction mass-balance row 3.4 / 3.0 / 0.5 / -3.6 across Re 30 → water; 3.5-4.0 in every run with or without a valve	F3 files; pinch_defaultpath 0842	sampling artifact of that row; fence
kernel sweep: U/U Saffman 0.894/0.956/0.973 at σ 0.25a; 0.899 production; 0.75-0.79 at σ = a; dt converged; core growth 2-24%	jelly_ring_kernel_sweep.py, run of 8 Sep (27 rows)	model output
bell body: 0.736/1.150/1.499 mN·s; 2.04×; jet 43-47 mm/s; rings at (0.94, +0.25) and (0.88, +0.2) R; cycle-4 jump 0.092 N·s, 390 mm/s	jelly_bell_body.py runs 2-3 (unstable work in progress)	WITHDRAWN — leaky apex, tethered, no margin
apex leak 220-230 in / ~500 out vs 297 cm ³ /s; distributed panels 296.3-297.9 vs 297.1; jet 22-25 mm/s	jelly_bell_sheet_stage1.py run of 8 Sep	model output
one stroke: impulse 12.4-13.3 mN·s (4%); shed Γ 1.25-1.51e-3 (unconverged); ring at (1.1, +0.17) R	jelly_bell_stroke_stage2.py run of 8 Sep	inviscid, tethered
margin thickness ~1 mm on 40 mm (0.025 D), flap ~0.1 D; δ = 1.25 mm at 100 mm; tip 52/38 mm/s; stopping vorticity 5→12→20 s ⁻¹	Gemmell, Costello & Colin 2014 Fig. 2 (Claude's measurement, ±0.2 mm) and text	SOURCED figure measurement / SOURCED text
starting Γ 0.774/0.798/0.810e-3 (3%); stopping Γ -0.88/-1.06/-1.19e-3 (20%); stopping vortex at (0.93, -0.15) R; net cycle impulse -2 to -4 mN·s	jelly_bell_cycle_stage3.py run B of 8 Sep	inviscid, tethered, 6 physical
free swim: U -29 / +15 mm/s; net 2.0-2.2 then 0.8-1.2 mm per cycle; added mass 550 g / body 55 g; residual 0.1-2%	jelly_bell_freeswim_stage5.py run of 8 Sep	inviscid, no drag
flap 30°/60°: tips 70/57, 106/98 mm/s; impulse +3.6-4.2 (contraction) / -6.6-9.0 (relaxation) mN·s; net ≤ 2.3 mm/s	jelly_bell_margin_stage6.py run of 8 Sep	ASSUMED flap waveform; volume check in that script invalid (recorded)
stopping vortex ~3× starting (5.50 vs 1.90, units as printed); 36 mm/s; 2.18 Hz; η 0.51; thrust 51/49	Neil and Askew 2018, J. Exp. Biol. 221: jeb191148, doi 10.1242/jeb.191148	SOURCED (full text; publisher record checked); units as printed
flap 17% of arc, passive, lags the bell; Robojelly bio flap +1340% thrust; starting-vortex Γ scales as a pitching panel	Villanueva, Vlachos & Priya 2014 PLoS ONE	SOURCED (full text)
stage 6b: lag 180° → -1.1/-0.4 mm/s (30°), backwards at 60°; lag 90° → -4.8/-3.4 (30°), -7.5/-6.3 (60°)	jelly_bell_margin_stage6b run of 8 Sep; reproduced digit-for-digit on the author's laptop 9 Sep	ASSUMED waveform
stage 7: added inertia 2.97 vs tissue 0.48 g·m ² ; lag 97°/90° at f_n/f 2/4; amplitude 91° → 7° with stiffness	jelly_bell_passive_flap_stage7 run B of 9 Sep	small-angle hinge; ζ = 0.2
kernel re-runs: dilation 6/32/115%; D/d 2 skin excess 182 mPa; ring slowing 0.95/0.90/0.79	jelly_vortex_ring_body_converged_run.txt (σ 0.25a, 57 blobs)	ASSUMED
edge sweep: G+ 1.00/0.80/0.59, G- -1.43/-1.06/-0.54 (×10 ⁻³) at δ 0.8/1.25/2.0 mm; net impulse -4.7/-3.6/-0.7 mN·s	jelly_bell_cycle_stage3 edge sweep of 8 Sep	model output
viscous stage 0: inviscid core growth 2.36 a σ^2 in 7.5 R; CS excess/law 0.98-1.00; PSE 0.96 → 1.01 (Re 300), 0.88 → 0.93 (Re 30) with lattice; PSE impulse drift 1-4%	jelly_viscous_ring_stage0 run of 9 Sep	$\delta \pm 0.2$ mm → ±15%
viscous stage 1 v4 (Re 3000, 25 s, laptop): particle-ruler baseline 0.382 a σ^2 ; impulse 6.6e-5; PSEax impulse 8.8e-3 vs plane 2.7e-2; excess/law 0.75-0.78 at Re 3000 after dividing by the 1.28 calibration	jelly_viscous_ring_stage1_20260909_0923_BEAR_v4.txt + r50 calibration	no remeshing
viscous stage 1 v5 (exact ruler; Re 3000/300/30; 25 / 2.5 / 0.3 s; laptop): remeshed inviscid baseline 0.151 a σ^2 in 10 R (16× cut vs 2.36); excess/law PSEax 1.013 /		SUPERSEDED by the v5 row below; ruler constant 1.28 / 1.44 measured against an analytic spread

1.009 / 0.968, PSE 0.962 / 0.986 / 0.949; impulse drift PSEax +8.8e-3 vs PSE +2.7e-2 at Re 3000; circulation drift -1.0e-2 both kernels at Re 3000; per-remesh floor 4-5e-5; U/U_Saffman 0.977-0.983 viscous vs 0.918 baseline	jelly_viscous_ring_stage1_20260909_1035.txt (the author's laptop, v5)	model output; V1d CLOSED
rung 1 grid: 17 ms/step at h = 1 mm; central flux unstable (5.6 ao ² , U 1.36 over 3,210 steps); QUICK: inviscid 10 R growth 0.038 ao ² , impulse -6.7e-4, U 0.987; Re 30 excess 1.007; Re 300 excess 1.108 (1 mm) / 1.125 (0.5 mm); diffusion-only 0.997 planar / 1.033 ring discriminator: Re 300 PSEax excess/law 1.009 / 1.063 / 1.082 at lattice ao/3 / ao/4 / ao/6; h ² extrapolation 1.13 / 1.10; inviscid baselines 0.032 / 0.012 / -0.000; PSEax impulse +7.2e- 4, circulation -6.9e-4 at ao/6	jelly_viscous_grid_rung1 container pieces of 9 Sep (piece A truncated, row from live output)	model output; Re 3000 and 0.5 mm set not yet done from the laptop
rung 1 grid, the author's laptop (h = 1 mm): rows identical to the container's; Re 3000 excess/law 1.150, U 0.971, circulation -2.6e- 3, impulse -4.3e-4, baseline 0.069 ao ²	jelly_viscous_ring_stage1_20260909_1035 / lattice4_1329 / lattice6_1329 (the author's laptop)	model output; V3d CLOSED
rung 2 wall, Re 300, h = 1 mm: free - impulse 1.0000 throughout, circulation 1.000 -> 0.936, U 14.0 -> 6.9 mm/s; walled - wall sheet 0.033 at start, secondary 0.31 at 1.15 R and 0.57 at stall, radius 1.00 -> 1.38 R at stall, stall at 0.784 R (t ≈ 21 s), primary 0.61 at stall / 0.50 at end vs free 0.95 / 0.94	jelly_viscous_grid_rung1_20260909_1237.txt, reproduced by _1511	model output; 0.5 mm check not yet done
rung 2 WATER, Re 3000, h = 0.5 mm: free - impulse 1.0000, circulation 0.9986 at 23 s; walled - stall 0.388 R at 15.4 s, radius 1.55 R at stall / 1.84 max, secondary 0.80 at stall / 1.05 at end, primary 1.00 at stall / 0.80 at end, rebound to 0.58 R at 18 s, second approach 0.40 R at 21.7 s; 3802 + 2742 s measured	jelly_viscous_grid_rung2_wall_re300_20260909_1601.txt (the author's laptop; WALL block identical to _1517)	model output; 3 cells per boundary layer; prior art abstract-level
rung 3, Re 300, 1 mm: stopping vortex -3.2e- 3 at 0.9 T at (0.75, -0.09) R, -29% in 0.5 s rest; water 1 / 0.5 mm: -4.5 / -4.4e-3, ~-1% in 0.5 s; starting ring 2.2-2.4e-3 (3x stage 3)	jelly_viscous_grid_rung2_wall_water_05mm_20260912_0002.txt (the author's laptop)	model output; 3-4 cells per layer
rung 4, Re 300: U/U_Saffman 1.046 / 1.038 / 1.014 / 0.927 at swirl 0 / ¼ / ½ / 1; readability 38% at 1 R, 6% at 10 R; water: 0.39-0.40 of launch spin at ~9 R, price -0.7 / -2.3 / -8% speed	rung-3 run files of 9 Sep 18:38 / 18:54 / 19:02 (the author's laptop); v3 container proof of 10 Sep within 1-3%	model output; tethered, one cycle; 3 cells/layer tank, 1-2 water
rung 5a, flap off, 4 cycles: W -24 / +21 mm/s; net +0.06 R/cycle mouth-first at Re 300, +0.04-0.07 in water	jelly_viscous_grid_rung4_swirl_re300_1mm_20260910_2237.txt, ... _water_1mm_20260910_2322.txt	model output; axisymmetric stability only
rung 6 all on: -0.115 / -0.217 / -0.204 / -0.189 R per cycle; lip off -0.015 to -0.019; plug off -0.03 to -0.05; shape off -0.07 / -0.16 / -0.23 / -0.17	..._rung5_free_noflap_4cyc_20260911_1213.txt, ..._water_20260911_1526.txt	trend; first- order coupling; impulse table untrustworthy, read W and distance
pinch (eps 0.45, no plug), 1 mm, 4 cycles: -0.30 R by 0.4 T, refill +50 mm/s, net +0.068 / +0.026 / +0.029 / +0.025 R; wake G+ 54e-3, G- -62e-3	..._rung6_animal_all_4cyc_20260911_1914.txt and the three switch-off files of 19:42	trend; mass- balance column not a check with lip/plug on
slow return (duty 0.2), 2 mm, 1 cycle: refill +15 mm/s, net +0.065 R vs +0.125 fast at 2 mm	..._moonjelly_pinch_4cyc_20260911_2136.txt	trend
slow return (duty 0.2), 1 mm, 3 cycles: -0.051 / -0.055 / -0.047 R per cycle (-0.026 R/s); refill +12.7 mm/s; wake G+ 22e-3, G- -31e-3; author's laptop) 4441 s measured	..._pinch_slowreturn_2mm_1cyc_20260912_container_proof.txt	coarse proof - WRONG IN SIGN against the 1 mm row; retired as a sign indicator
slow return (duty 0.2), 0.5 mm, 2 cycles: -0.119 / -0.134 R per cycle (-0.060 / -0.067 R/s); refill +11.4 mm/s; wake G+ 21e-3, G- -24e-3; 33571 s measured (shared machine)	jelly_viscous_grid_rung6_animal_moonjelly_pinch_slowreturn_3cyc_20260912_0812.txt (the jelly_viscous_grid_rung6_animal_moonjelly_pinch_slowreturn_05mm_2cyc_20260912_0947.txt (the author's laptop)	trend; first- order coupling; lower bound (see 0.5 mm row) sign confirmed; walk 2/1/0.5 mm = +0.065 / -0.051 / -0.119, not converged
slower return (duty 0.1, period 4 s), 1 mm, 3 cycles: -0.232 / -0.250 / -0.300 R per cycle (-0.058 / -0.062 / -0.075 R/s); refill +3.5 mm/s; 8967 s measured	jelly_viscous_grid_rung6_animal_moonjelly_pinch_slowreturn_duty01_3cyc_20260912_0946.txt (the author's laptop)	trend; first- order coupling; lower bound (see 0.5 mm row) sign confirmed;
slower return (duty 0.1), 0.5 mm, 2 cycles:		

-0.386 / -0.395 R per cycle (-0.097 / -0.099 R/s); 69,532 s measured (shared)	...moonjelly_pinch_duty01_05mm_2cyc_20260912_2237.txt	1.6× the 1 mm value; steady
leash, 1 mm, 3 cycles: 40/60 rocker J -85.9 / -86.1 / -84.8 mN s (push -86, return ~0); slow stroke J -93.9 / -96.5 / -96.5 (push -88, return -8); snap mirror J -8.1 / -70.6 / -64.5 per 2 s	...tether_duty04/duty01/mirror_3cyc_20260913_1212.txt	trend; thrust at zero speed; 0.5 mm check running
one-way apex valve 0.3 R, 1 mm: tethered rocker J -86.4 / -100.9 / -92.2; free rocker +0.040 / +0.012 / -0.020 R per cycle; free slow stroke -0.574 / -0.649 / -0.572 R per cycle (-0.15 R/s)	...tether_duty04_valve03..., ...free_duty04_valve03..., ..._free_duty01_valve03_3cyc_20260913_1212.txt	trend; ideal valve; model unstable in three neighbouring runs (held bell; 0.2 R cap)
lip phase, duty 0.1, 1 mm, 3 cycles: lag -0.06 → -0.100 / -0.215 / -0.091; -0.03 → -0.217 / -0.376 / -0.214; +0.03 → +0.357 / +0.332 / +0.155; +0.06 → +0.538 / +0.506 / +0.519	the four ..._duty01_lag*_3cyc_20260913_1019.txt files	trend; the cliff
slowest return (duty 0.05, period 8 s), 1 mm, 3 cycles: -0.518 / -0.483 / -0.541 R per cycle (-0.065 / -0.060 / -0.068 R/s); body coasts to rest by ~4 s; 27413 s measured (shared)	..._slowreturn_duty005_3cyc_20260912_1353.txt	trend; per-second ceiling reached; forgetting time ≈ 4 s
Re 100 pace pair (v 3e-5, 1 mm, 3 cycles): fast +0.110 / +0.070 / +0.088; slow +0.012 / -0.009 / -0.026 R per cycle; 3814 s and 6787 s measured (shared)	..._x0_re100_fastreturn/slowreturn_3cyc_20260912_1939.txt	trend; the slow return's sign flip sits near Re 100
Re 30 pace pair (v 1e-4, 1 mm, 3 cycles): fast return +0.122 / +0.119 / +0.135; slow return +0.056 / +0.049 / +0.055 R per cycle; 2399 s and 4823 s measured	..._x0_re30_fastreturn_3cyc_20260912_1032.txt, ..._x0_re30_slowreturn_3cyc_20260912_1032.txt	trend; pace-dependent, sign-independent at Re 30
mirror stroke (1.6 s in / 0.4 s out, period 2 s), 1 mm, 3 cycles: Re 30 +0.087 / +0.024 / +0.019; Re 300 +0.133 / -0.579 / -0.648 R per cycle; 6316 s and 6885 s measured (shared machine)	..._mirror_re30_3cyc_20260912_1352.txt, ..._mirror_re300_3cyc_20260912_1352.txt	trend
mirror stroke, Re 300, 1 mm, 6 cycles: +0.135 / -0.581 / -0.648 / -0.634 / -0.646 / -0.619 R per cycle (-0.31 R/s steady); W -39 / +69 mm/s repeating; 13786 s measured (shared machine)	..._mirror_re300_6cyc_20260912_1556.txt	steady state reached; 0.5 mm check not yet done; lower bound
frequency axis (duty 0.4), 1 mm, 3 cycles: period 2 s +0.105 / +0.060 / +0.060; period 0.5 s +0.046 / -0.001 / +0.034 R per cycle (1 s of record: +0.068 / +0.026 / +0.029 / +0.025); 3660 s and 3793 s measured	..._freq_t2_3cyc_20260912_1816.txt, ..._freq_t05_3cyc_20260912_1816.txt	trend; ≈ +0.03 R/s at all three periods
Re 3 pace pair (v 1e-3, 2 mm, 3 cycles): fast +0.026 / -0.007 / -0.017; slow -0.022 / -0.044 / -0.043 R per cycle; 1057 s and 2016 s measured	..._x0_re3_fastreturn_3cyc_20260912_1352.txt, ..._x0_re3_slowreturn_3cyc_20260912_1352.txt	trend; 2 mm honest at this Re (layer 5 cm)
lip lag ±0.15, Re 3, 2 mm: +0.059 / +0.026 / +0.024 and +0.056 / +0.042 / +0.039; Re 300, 1 mm, duty 0.4, lag +0.15: +0.183 / +0.153 / +0.136 R per cycle	the three ..._lag*_3cyc_20260912_1531.txt files	trend; geometric part ~±0.01 at Re 3; trailing lip pumps at Re 300
lip lag ±0.25, Re 3, 2 mm: +0.085 / +0.086 / +0.078 and +0.111 / +0.064 / +0.087 (geometric part ≈ -0.005, below the tool's floor); Re 300, duty 0.1, lag -0.15: +0.137 / +0.190 / +0.221 R per cycle — a growing pump where lag 0 swims at -0.25	..._lagP025/lagM025_3cyc_20260912_2018.txt, ..._re300_duty01_lagM015_3cyc_20260912_1716.txt	trend; lag 0 optimal at Re 300 in both directions
leash, resolution and viscosity: rocker 0.5 mm J -87.9 / -90.2; Re 30 -58.6 / -70.6 / -71.2 (return +15); water v 1e-6 0.5 mm -96.5 / -93.9; 7.6 s return held -94.2 / -95.0 / -94.9 (return -8.2)	...tether_duty04_05mm..., ...tether_re30_duty04..., ...tether_duty04_water_05mm..., ...tether_duty005_3cyc...	converged at 1 mm; stroke number across two decades of v
leash, 0.2 s push: 0.8 s return -189 / -193 (0.5 mm -195 / -203); 3.6 s return -191 / -193 / -193 (push -177, return -16)	...tether_contraction_02s_1s_3cyc..., ...tether_contraction_02s_1s_05mm_2cyc..., ..._tether_contraction_02s_return36s_3cyc_20260914_1447.txt	converged; impulse ∝ rim speed; recapture 8%
comb on the leash, 0.4 s push held, periods 1 / 1.4 / 2.0 / 2.8 / 4 / 5.4 / 8 s: -85 / -97 / -99 / -98 / -96.5 / -95.6 / -95 mN s (settled)	..._tether_return10/16/24/50_3cyc_20260914_1515.txt + the three duty files	flat ±3%; no tooth
launch-and-lean, 0.8 s squeeze held, snap 0.4 / 0.3 / 0.2 / 0.1 s: -76 / -104 / -168 / -350 mN s per settled cycle; 0.1 s at 0.5 mm: -37.4 then -428.0	..._tether_snap_return04/03_3cyc_20260914_1827.txt, ...tether_contraction_08s_1s..., ...tether_snap_return01_3cyc..., ..._tether_snap_return01_05mm_2cyc_20260914_2256.txt	∝ 1/snap; corrects up ×1.22
push axis at the 3.6 s return, 1 mm: 0.3 s -0.347 / -0.530 / -0.441; 0.15 s -0.779 / -0.782 / -0.748; 0.2 s at 0.5 mm -0.863 / -0.835 R per cycle (-0.23 R/s)	...contraction_03s_return36s..., ..._contraction_015s_return36s_3cyc_20260914_1447.txt, ..._contraction_02s_return36s_05mm_2cyc_20260914_2256.txt	trend; bend real; fast push corrects up ×1.28
fast push's returns, 1 mm: 1.6 s -0.272 / -0.165 / -0.245; 2.4 s -0.450 / -0.409 / -0.570; 5.0 s -0.864 / -0.745 / -0.557 R per cycle	...contraction_02s_return16s..., ...return24s..., ...return50s_3cyc...	trend; knee between 1.6 and 2.4 s

push duration at 3.6 s return, 1 mm: 0.2 s -0.662 / -0.757 / -0.593; 0.8 s -0.003 / -0.063 / -0.064 R per cycle	...contraction_02s_return36s..., ..._contraction_08s_return36s_3cyc_20260913_1853.txt	trend; animal family, correction upward ($\times 1.28$ measured for the 0.2 s push)
return 5.0 s (duty 0.074), 1 mm: -0.343 / -0.304 / -0.503 R per cycle (-0.064 / -0.056 / -0.093 R/s)	...moonjelly_pinch_duty0074_3cyc_20260913_1641.txt	trend; the plateau
sea nettle (plug on, eps 0.2), 0.5 mm, 2 cycles: -0.099 / -0.219 R per cycle (1 mm: -0.115 / -0.217)	...nettle_allon_05mm_2cyc_20260913_2155.txt	converged at 1 mm for the plugged animal
one-way valve 0.4 R on the slow stroke, free, 1 mm: -0.713 / -0.814 / -1.109 R per cycle (growing)	...free_duty01_valve04_3cyc_20260913_1725.txt	trend; model tag as above
fidelity: 16/16 PASS legs 1-3 (11 Sep); leg 6 5/5 digit for digit on v1.4 through v1.9.2 (12- 13 Sep)	jelly_fidelity_check run files	tolerance 5%; one-cycle leg — a two-cycle leg is not yet done
boundary layer $\sqrt{\nu T}$: 1.0 / 3.2 / 10 mm at ν 1e-6 / 1e-5 / 1e-4, $T = 1$ s; stage-3 ring Re $\Gamma \approx$ 800; grid 2.4e5 cells at $h = 1$ mm, 9.6e5 at 0.5 mm; 100 / 200 steps per cycle at CFL 1, u 0.1 m/s	recomputed for the stage-2 plan b	arithmetic SOURCED; $u_{\max}$, CFL ASSUMED
ring signature: E 0.377 vs 0.403 mJ; U 0.963 Saffman; H/Γ^2 0.63 at swirl 0.2U; $\Gamma_{\max}$ 1e-2 m ² /s per stroke at L/D 4	jelly_ring_signature run of 9 Sep	axisymmetric: $W_r = 0$ by construction dead band 1% R
ternary template: starting .-.-.-.-0000 / .-0+---- -; stopping ...0-+++0 / ...0-.-.-.-	jelly_ring_ternary run of 9 Sep	SOURCED (abstract, scanned page)
prey entrainment: capture of prey slower than the margin flow; escape above it; scaling with bell diameter 0.8-7.1 cm	Costello & Colin 1994 Mar. Biol. 121	
material wave speed $\sqrt{E/\rho}$ 0.316 m/s at 100 Pa; muscle activation wave 0.474 ± 0.132 m/s ($n = 6$, 0.319-0.672); turning rate 76 $\times$, circulation asymmetry 34 $\times$ at resonance; 4 cm model, $\Delta x = L/1024$	Hoover et al. 2021 PNAS	SOURCED (full text read)
0.74 vs 0.32 Pa (2.3 $\times$); thrust 2.7 $\times$; +41% speed, +61% distance; 18-26 mm/s	Gemmell et al. 2021 Proc. R. Soc. B	SOURCED (full text, results read)
margin p 0.76 $\times$ at -0.5 Γ , negative peak at -1.0 Γ ; primary 0.92 / 0.79 of Saffman; same- sign +0.5 $\Gamma \rightarrow$ 1.31 (+31%), p 1.74 $\times$; counter ring 1D behind 1.14 $\times$	jelly_virtual_wall.py, run of 8 Sep (this rebuild)	inviscid, bench scale R 5 cm
vortex particles + Brinkman penalization; 2 or 3 rings per stroke; speed $\propto \sqrt{Re}$	Rasmussen et al. 2009 arXiv	SOURCED (abstract)
IB2d 2-D IB-FSI; LBM Re 70-400, recapture Re-dependent, rigidity raises CoT	Taheri 2018; Dawoodian et al. 2021	SOURCED (front / OCR full text); 2-D caveat
ring dilation 6/33/117%; slip 47/58/67 mm/s; 0.89 Saffman	jelly_vortex_ring_body.py	model output, inviscid
self-timer quantisation; re-lock in one cycle	jelly_self_timer_sim.py	lumped model
nose 3.8 q; equator -7/-10/-19 q; skin 50/66/400 Pa field	jelly_vortex_ring_body.py (O2)	inviscid, unsteady Bernoulli
rim deviation 57 / 4 / 0 mPa; SNR 31 / 2; 2.7 s early	jelly_rim_deviation.py	inviscid
arrival delay 0.7 / 1.4 / 3.6%; τ 1.95 / 1.98 thresholds; 2% jitter	jelly_pacemaker_detector.py	inviscid; jitter ASSUMED
shed 50-80% regardless of fraction; primary stalled to 0.08-0.37	jelly_secondary_ring.py	heuristic — recorded failure
328 kg / 3 t lift; 29 N/m; 3 s	jelly_inverted_ballute.py	SOURCED gas law
ladder thrusts/powers; platform loads; 7/18 bells	jelly_use_case_ladder.py	ASSUMED model, SOURCED drag
Jupiter ρ 0.17; ν ratio 1.7	recomputed	ASSUMED inputs / UNVERIFIED
Shapere & Wilczek 1989; Moffatt 1969; Colin 2010; Schultz 2023; Mackie & Meech (Aglantha); Costello & Sutherland 2015 (Nanomia); Sashida; Pelamis, Yamato-1, Slocum, DP/MOB figures; 1-5 Hz ambient	memory	UNVERIFIED: not checked against a source; used only as a scale, never for a claim

Every model number regenerates from the named script via its RUN_*.bat. Tools of record for the rows of 16-17 September:
jelly_viscous_grid_rung6_animal.py v2.0 (sha256 2eae8352...) for the run day of 16 September and v2.2 (sha256 8f21f014...) for the F3 batch, with
jelly_fidelity_check.py v1.7; every laptop run file is UTF-16 as the laptop writes it. Scripts of record (8 September): jelly_hL_scan, jelly_slug_engine,
jelly_spring_q, jelly_matriarch_budget, jelly_oam_torque, jelly_acoustic_null, jelly_ring_body_bench, jelly_use_case_ladder, jelly_self_timing,
jelly_inverted_ballute, jelly_pair_cancel, jelly_pair_sensitivity, jelly_self_timer_sim, jelly_vortex_ring_body, jelly_rim_deviation, jelly_pacemaker_detector,

jelly_secondary_ring, jelly_virtual_wall, jelly_ring_kernel_sweep, jelly_bell_sheet_stage1, jelly_bell_stroke_stage2, jelly_bell_cycle_stage3, jelly_bell_freeswim_stage5, jelly_bell_margin_stage6, jelly_bell_margin_stage6b, jelly_bell_passive_flap_stage7, jelly_kernel_rerun, jelly_kernel_rerun_pieces, jelly_viscous_ring_stage0 (v5), jelly_viscous_ring_stage1 (v6, lattice argument), jelly_viscous_grid_rung1 (numpy), jelly_viscous_grid_rung2_wall (numpy), jelly_viscous_grid_rung3_bell (v3, GMRES penalization), jelly_viscous_grid_rung4_swirl, jelly_viscous_grid_rung5_free_WIP (trend tool; passive flap open), jelly_viscous_grid_rung6_animal (v1.9.2, frozen 13 September: duty, period-pin, lip-lag, tether with an impulse ledger, one-way valve; event-time column; per-cycle time step), jelly_fidelity_check (v1.3), jelly_verify_manifest (v1.2), jelly_ring_ternary, jelly_ring_signature; jelly_bell_body is superseded by the stage scripts and is not of record; the interactive JELLY_BELL_ENGINE_TOY_20260907.html is illustrative only.

Declaration

Matthew “Bear” Schulz · ORCID 0009-0000-0956-5743 · independent researcher, Belmont, California

What this document is

This is a preprint and a checkpoint on a road, not a destination. It has not been peer reviewed. It is the work of a part-time, unfunded, free-to-the-world research effort, and it is published so that its measurements, its instrument and its failures are available to anyone who can use them or correct them. Where it is wrong, the record on which it is published will carry the correction.

The literature pass is limited, and says so

The prior art named in this paper was located at the level of abstracts and extracts, not read in full, and no systematic review was performed. The references the paper leans on were checked against their publisher records: the scallop theorem is Purcell’s (1977, Am. J. Phys. 45:3–11; record not re-fetched in this pass); the swimming holonomy is Shapere and Wilczek’s (1989, J. Fluid Mech. 198:557–585); the formation number is Gharib, Rambod and Shariff’s (1998, J. Fluid Mech. 360:121–140); the medusan stopping vortex and passive energy recapture — 30 percent further per cycle, a 48 percent improvement in cost of transport, thrust from positive pressure under the bell during refill — are Gemmell, Costello, Colin, Stewart, Dabiri, Tafti and Priya (2013, Proc. Natl. Acad. Sci. 110(44):17904–17909, doi 10.1073/pnas.1306983110); the jet-paddling stopping-vortex recapture in a rhizostome is Neil and Askew (2018, J. Exp. Biol. 221: jeb191148, doi 10.1242/jeb.191148); ctenophore stealth is Colin, Costello, Hansson, Titelman and Dabiri (2010, Proc. Natl. Acad. Sci. 107(40):17223–17227, doi 10.1073/pnas.1003170107). The closest prior instrument to this paper’s, found at abstract level while checking the above, is the swirl-free axisymmetric Navier–Stokes solver applied to a prolate and an oblate hydromedusa by Sahin, Mohseni and Colin (2009, J. Exp. Biol. 212); this paper’s solver was written without knowledge of it and is not compared to it here, and that comparison is an open question. Every other name in the appendices is a pointer recalled from memory, marked as such, and relied on for no measured claim. The animal’s frames in Appendix A are the author’s own stills. Adjacent work is prior art, not a rival: where this paper’s instrument agrees with published measurement it says so, and where it cannot reach a published result — an experiment, a three-dimensional flow — it says that too. Any reader who knows of work this paper should have cited is asked to write.

Assistance from an AI system

The simulation tools, the analysis scripts, the run-day bookkeeping and the drafting of this document were carried out with an AI assistant (Claude, Anthropic) working under the author’s direction. The author set the questions, the strokes, the acceptance bars and the verdict vocabulary; the assistant wrote and ran code, read results from run files, and drafted prose that the author edited. Every number in the paper regenerates from a named script and a named run file (§13), and the author takes responsibility for every claim. The assistant is not an author.

The limits, stated loudly

The instrument is an axisymmetric finite-difference solver: a stream function in the radial and axial coordinates, so every vortex line is a circle about the axis and nothing in it can knot, link or wobble off-axis. It has a measured floor: a rigid reciprocal squeeze with a massless body at a Reynolds number near one moves 0.085 radii per cycle where the scallop theorem demands zero, so no displacement below that is read as swimming and every zero-memory quantity is held (§11). One-millimetre runs under-read water viscosity by five to six percent against half-millimetre runs; four-millimetre runs are trends only and their signs are not read. The mass-balance column is not read at the end-of-contraction row. Three-cycle runs are not steady state for the launched wake. No experiment was performed; every result is a model output, labelled as such in §13.

Dual use, stated with the capability

The finding that a bell can keep station on its own wake with almost no net motion, and the through-flow “duct” mode that a valved bell can enter, describe mechanisms that could inform the design of quiet, low-signature unmanned underwater vehicles. That is a civil capability (station-keeping sensors, environmental monitoring, cable and hull inspection) and a military one (loitering surveillance). The paper gives mechanisms, non-dimensional numbers and an instrument, not a device: no hull geometry, actuator, power system or control law is specified beyond what is needed to reproduce the simulations. The governance remedies the author supports are the ordinary ones for open research at this level: publication in the open so that the capability and its limits arrive together; no export of hardware specifications from this record; and the statement, here, that the erratic duct mode is unstable in the free body and is not a design.

Provenance

Every number in this paper names the run that produced it and moves when the run does. The full provenance table is §13. Tools of record for the September 2026 runs: `jelly_viscous_grid_rung6_animal.py` v2.0 (sha256 2eae8352fd6b47b9...), v2.2 (8f21f0148558dcef...) and v2.3 (90f05d0565695890...), each reproducing the previous version’s physics digit for digit on the fidelity legs; `jelly_fidelity_check.py` v1.8. The tools, their launchers and every run file cited are deposited beside this document under CC BY 4.0.