# ENERGETICS OF THE OSCILLATING FIN THRUSTER

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**Abstract**

We examine the energetics of flexible oscillating fin thrusters. We find that under certain conditions, the thrust to power ratio reaches 1N/W including motor losses. We attribute this high efficacy to the thruster's ability to store and recover energy.

**Introduction**

Development of flexible Oscillating Fin Thrusters (f-OFT) began as an effort to produce fish-like thrust using simple mechanical systems. It was quickly found that controlled delivery of thrust is possible using a single actuator. Recently, an f-OFT hovering module was integrated on FAU's Morpheus and enabled panoramic sweeps, stopping, and station holding maneuvers (Figure 1).

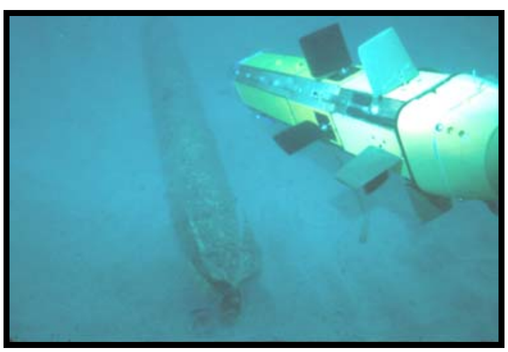


**Figure 1. Four f-OFT thrusters mounted amidships on FAU's Morpheus drive 360° scan maneuvers.**

Our progress in control and deployment of multi-OFT vehicles is described elsewhere.[1] In this article we focus on the energetics of f-OFTs.

The question we address in this article is whether f-OFTs are efficient or inefficient in comparison with marine thrusters. Initial results indicated that f-OFTs have a Bollard efficiency of 30%, independent of oscillation frequency and amplitude.[2] In comparison, commercial propeller-based marine thrusters have a Bollard efficiency of 50%.[2] Because this study was limited to single fins, we examined the effect of fin shape, and found that for selected geometries the efficiency is 50%.[1] Recently, we examined the higher-efficiency geometries in more detail and found that the efficiency in fact reached 75% at high frequency. This indicates that properly optimized, f-OFTs are more efficient than marine thrusters.

In this article we present these recent results. We show that the high efficiency of f-OFTs is due to their elasticity, and is the result of resonant transfer between the bending of the fin and the kinetic energy of the OFT.

**f-OFT performance**

We distinguish between fin-only and overall system efficiency. Fin-only efficiency is that which would be achieved if the motor were perfect. It is a measure of the thruster's ability to transfer momentum to the fluid. Overall system efficiency is that which is achieved when drivetrain losses are included. It is a measure of the thruster's drain on a vehicle's power plant. The two numbers are equally important, yet they are generally different. All data in this section excludes drivetrain losses; the next section analyses the effect of losses.

A series of eight f-OFTs of different shapes were mounted on a six-axis load cell and were subjected to a sinusoidal profile:

$$\theta(t) = A\cos(2\pi ft) \qquad (1)$$

where $\theta(t)$ is the pitch angle at time $t$, $A$ is the half-width oscillation amplitude, and $f$ is the oscillation frequency. We collected time-resolved loads at $f$ = 4, 5 and 6hz, and $A$ = 10, 15, 20, 25, and 30 degrees.[3] We then extracted time-averaged thrust and power as:

$$T = f \int_0^{1/f} dt\, T(t)$$
$$P = f \int_0^{1/f} dt \dot{\theta}(t) \tau(t) \qquad (2)$$

where $\tau$ is the measured axial torque, $T$ is thrust, and $P$ is power.

Examination of the data shows that f-OFTs operate in either a high or a low efficiency mode depending on frequency, shape, and stiffness. For specificity, the high efficiency data is from a 6"x6", NACA 0014, shore A 40 polyurethane fin operating at f=6hz. The low-efficiency data is from a 6"x4", NACA 0014, shore A 40 polyurethane fin at the same frequency.

The high and low-efficiency thrust-power curves are compared in Figure 2. At high efficiency, thrust increases non-linearly, and T/P ranges from 0.8 to 2 N/W. The Bollard efficiency (not shown) ranges from 50% at high power to 75% at low power. At low efficiency, thrust increases linearly at a rate of 0.4N/W. The Bollard efficiency (not shown) is 30%, independent of power.

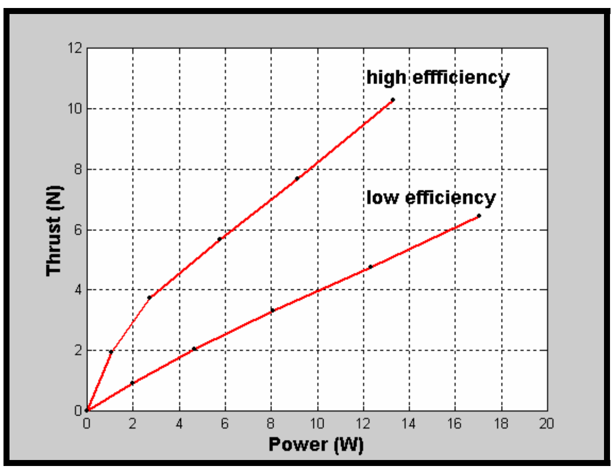



**Figure 2: Thrust-Power curve in high and low-efficiency modes. At high-efficiency, the dependence is $P^{0.6}$. Data collected at 6hz on 6"x6" (high) and 6"x4" (low) fins.**

The transition from low to high efficiency is sharp. Versus aspect ratio at constant frequency and oscillation amplitude (Figure 3), thrust/power changes abruptly from 0.5N/W at $AR$=1.4 to 2N/W at $AR$=1 versus. Versus frequency at constant aspect ratio and oscillation amplitude, similar changes are seen (Figure 4).

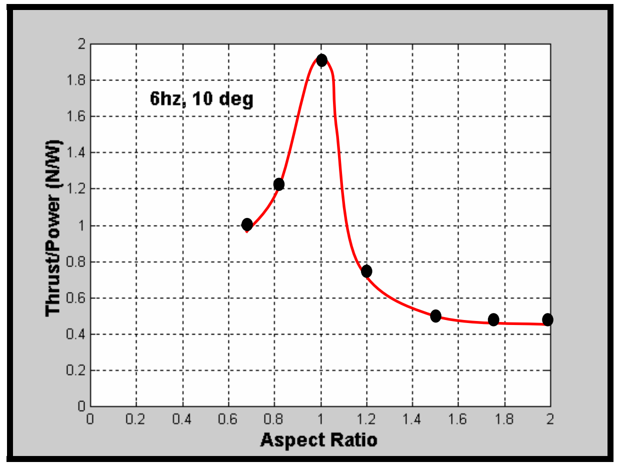



**Figure 3: Thrust/Power ratio versus aspect ratio at fixed frequency and amplitude.**

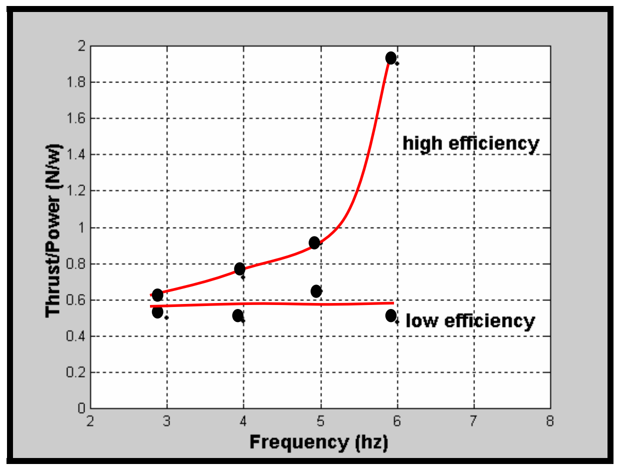



**Figure 4: Thrust/Power ratio versus frequency in high and low-efficiency modes. Note that the high-efficiency ratio should fall-off at higher frequencies.**

We now turn to the issue of mechanism. Figure 5 shows that at high-efficiency, 40 to 60% of the energy is recovered in the latter part of the stroke. At low efficiency, less than 7% is recovered. Thus, high efficiency is due to energy recovery. Figure 6 shows that the high rate of recovery is due to the torque being in quadrature with the angular velocity; at low efficiency, torque and speed are in phase. This shows that at high efficiency, f-OFTs are slightly damped harmonic oscillators.

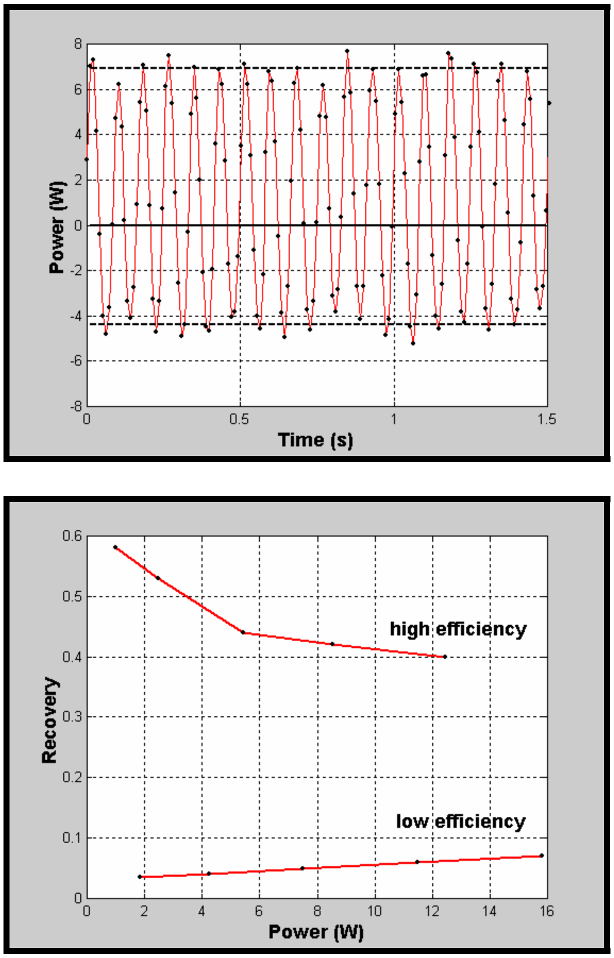


**Figure 5: Top: power trace at high efficiency. Bottom: recovery ratio for high and low-efficiency, defined as the ratio of area below 0 (energy recovered) to the area above (work done).**

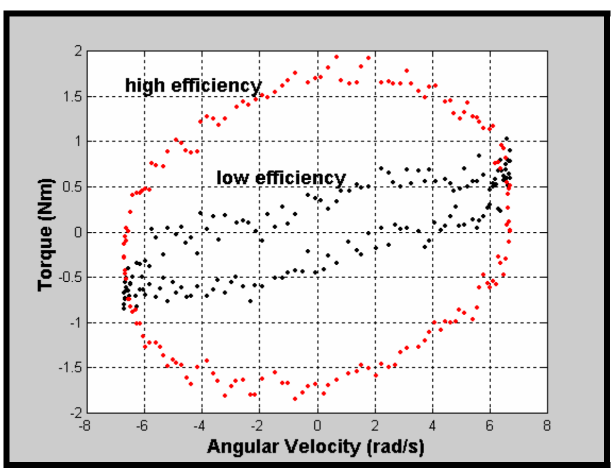


**Figure 6. Torque-velocity diagram. At low efficiency operation (black), torque and speed are in phase. At high efficiency (red), they are in quadrature.**

The data suggests a picture of resonant transfer between the kinetic energy of the shaft and the bending energy in the fin. During the first part of the stroke, the fluid bends the fin and the f-OFT stores energy; during the last part, the fin returns that energy as the load vanishes. If the fin relaxation time matches the oscillation frequency, the fin transfers its energy to the shaft. If the frequency of relaxation is larger or smaller than the oscillation frequency, the bending energy is released out of phase and is not recycled.

## Drivetrain Losses

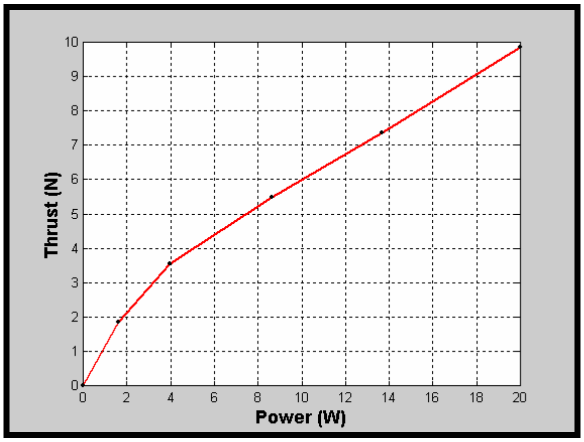
We now address the issue of drivetrain losses. The equations of motion of an f-OFT including motor and fin motion are:

$$
\begin{aligned}
V &= Ri + L\frac{di}{dt} + gK_T\omega \\
J\frac{d\omega}{dt} &= \eta g\left(K_T i - F\omega\right) - \tau_{fluid}
\end{aligned}
\tag{3}
$$

where $i$ is the motor current, $\omega$ the OFT angular velocity, $V$ the source voltage, $R$ the winding resistance, $L$ the winding inductance, $g$ the gear ratio, $K_T$ the motor torque constant, $J$ the combined axial moment of inertia of the fin + motor + gearbox, $\eta$ the gearbox efficiency, $F$ the viscous friction coefficient of the motor, and $\tau_{fluid}$ the torque applied by the fluid to the f-OFT.

The torque recorded by the load cell is related to the fluid torque by $\tau_{measured} = \eta g\left(K_T i - F\omega\right)$. From $\omega$ and the measured torque, we can therefore isolate the individual contributions to torque and power and predict the performance of any OFT-motor assembly.

Figure 7 shows the thrust-power curve and the power budget of a properly sized motor f-OFT. In contrast to Figure 2, this plot includes all losses. At A=30°, the f-OFT produces 10N of average thrust. The average power needed to run it is 20W. Power is used as follows: 13W to the fluid (65%), 4W in gearbox losses (20%), and 3W in ohmic losses (15%). Viscous losses are negligible. Including all losses, the cost is 2W per Newton. This should be compared with typical marine thrusters which use 5W/N.



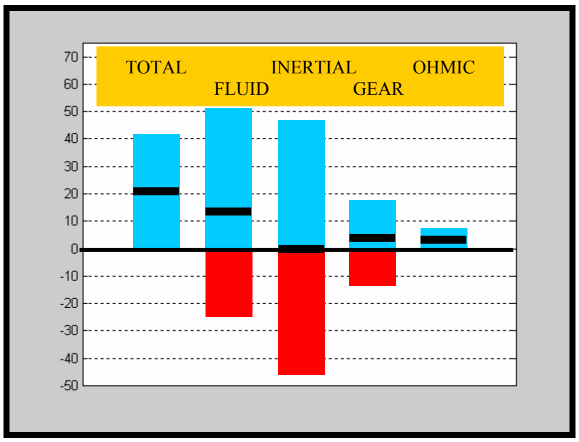




**Figure 7. Top: thrust-power curve for a 6"x6" OFT operating at 6hz. Bottom: power budget at 30°.**

**Discussion**

Properly optimized and sized, f-OFTs are very efficient thrusters. We measured thrust being produced at a rate of 0.8 to 2 N/W excluding motor losses, and 0.5 to 1N/W including them.

We find that f-OFTs recover 40 to 60% of their energy. This is the result of the elasticity of the fin. The data suggests a picture of resonant energy transfer between the bending energy of the fin and the kinetic energy of the shaft. It also implies that rigid OFTs cannot be made as efficient as flexible ones.

This argument can be made quantitative. Using phasor notation, the input torque is

$$\tau_{in} = 2\pi e^{i\pi} Af\left(2\pi Jf - \beta\right) \quad (4)$$

where $J$ is the axial moment of inertia of the OFT and $\beta$ is a constant determined by the shape and elastic properties of the fin. Here we've used the experimental observation that the fluid torque is bilinear in amplitude and frequency. By properly matching the moment of inertia $J$ of the motor with the fin through $\beta$, it is possible to zero out the input torque (except for losses). This argument suggests the existence of an optimal frequency for reach fin.

An argument could be made that the high efficiency of f-OFTs is due to wake capture: during the initial part of the stroke, the fin sets up a wake and recovers its energy at the end of the stroke.[4] We do not believe that wake capture is important here. If it were, small fin shape changes would have a small effect on energy recovery because small geometrical changes should produce small flow field changes. Figure 3 shows that small shape changes have in fact a large impact.

A number of robotic devices have made use of elastic recoil mechanisms for recycling energy during locomotion. Examples are the flying 6m wingspan ½-scale copy of the pterosaur *Quetzalcoatlus northropi* built by Paul MacCready et al. at AeroVironment,[5] the one-legged, 1m high, 3D hopping robot built by Marc Raibert's group at the MIT leg lab,[6] the bouncing hexapods Sprawlita of Stanford[7] and the hexapod RHex built in Martin Buehler's Ambulatory Robotics lab at McGill.[8]

The pterosaur[5] flapped its 3m wings with the help of an elastic element in series with its electric motor. The body of the craft had a tendency to drop beneath the plane of the wings, as it provided no lift on its own. Since this upstroke phase required little force, the rubber elastic element stored strain energy during the upstroke and returned it in concert with the electric wing flapping drive motor making up for strain energy losses on the downstroke.

Raibert's machine[6] hops continuously using a gas cylinder as a spring to store energy during the landing phase, returning it on the next jump. Once hopping, the only locomotive power the machine needs is that required to make up for the losses in the cylinder, or for programmed increases in gas volume and so jumping height.

In water, the situation remains unresolved. Despite ample modeling and evidence for elastic energy storage in the oscillatory locomotion of aquatic organisms, it has never been directly measured in a swimming animal. Though elastic elements have been incorporated in the design of some oscillatory swimming machines, we know of no other direct measurements of energy storage and return via elastic recoil in any aquatic system.

**Acknowledgments**

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**References**

1. B. Hobson et al., 2003, *Adding Terminal Navigation to the Morpheus AUV using Nektor Maneuvering Modules*, ONR final report.
2. M. Kemp et al., 2001, *Assessing the Performance of OFTs*, UUST 12.
3. The cell is a JR3 100M40A six axis cell with 0.1N resolution. Data was collected at 100hz. The test rig is mounted to the bottom of a 0.8m x 0.8m x 1m flow tank.
4. M.H. Dickinson, F.O. Lehman, S.P. Sane, 1999, *Wing Rotation and the Aerodynamics Basis of Insect Flight*, Science **282**, 1954; C.P. Ellington et al., 1996, *Leading-edge Vortices in Insect Flight*, Nature **384**, 626; Dickinson, 2001, *Solving the Mystery of Insect Flight*, Scientific American, **June**, 34.
5.Http://www.nationalgeographic.com/ngm/0105/feature5/zoom4.html
6. M.H. Raibert, 1985, *Four-legged running with one-legged algorithms*, Second International Symposium on Robotics Research, 311.
7. J.E. Clark et al. , 2001, *Biomimetic Design and Fabriation of a Hexapedal Running Robot*, Intl. Conf. Robotics and Automation.
8. U. Saranli, M. Buehler, and D. E. Koditschek, 2001, *RHex: A Simple and Highly Mobile Hexapod Robot*, Int. J. Robotics Research, **20**, 616.