

COMMUNICATION

Evidence of self-correcting spiral flows in swimming boxfishes

I K Bartol¹, M S Gordon², P Webb³, D Weihs⁴ and M Gharib⁵¹ Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529-0266, USA² Department of Ecology and Evolutionary Biology, University of California, Los Angeles, CA 90095-1606, USA³ School of Natural Resources and Environment and Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA⁴ Department of Aerospace Engineering, Technion, Haifa, 3200, Israel⁵ Options of Bioengineering and Aeronautics, California Institute of Technology, Pasadena, CA 91125, USAE-mail: ibartol@odu.edu, mvgordon@ucla.edu, pwebb@umich.edu, dweihs@technion.ac.il, mgharib@caltech.edu

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Abstract

The marine boxfishes have rigid keeled exteriors (carapaces) unlike most fishes, yet exhibit high stability, high maneuverability and relatively low drag given their large cross-sectional area. These characteristics lend themselves well to bioinspired design. Based on previous stereolithographic boxfish model experiments, it was determined that vortical flows develop around the carapace keels, producing self-correcting forces that facilitate swimming in smooth trajectories. To determine if similar self-correcting flows occur in live, actively swimming boxfishes, two species of boxfishes (*Ostracion meleagris* and *Lactophrys triqueter*) were induced to swim against currents in a water tunnel, while flows around the fishes were quantified using digital particle image velocimetry. Significant pitch events were rare and short lived in the fishes examined. When these events were observed, spiral flows around the keels qualitatively similar to those observed around models were always present, with greater vortex circulation occurring as pitch angles deviated from 0°. Vortex circulation was higher in live fishes than models presumably because of pectoral fin interaction with the keel-induced flows. The ability of boxfishes to modify their underlying self-correcting system with powered fin control is important for achieving high levels of both stability and maneuverability. Although the challenges of performing stability and maneuverability research on fishes are significant, the results of this study together with future studies employing innovative new approaches promise to provide valuable inspiration for the designers of bioinspired aquatic vehicles.

1. Introduction

Stability, which involves the prevention and correction of disturbances, and maneuverability, which involves the creation and amplification of disturbances, are mutually exclusive in most human-engineered vehicles (Goldberg 1988, Weihs 1993). However, in many fishes, the body and control surfaces work synergistically to achieve high

levels of both (Weihs 2002, Webb 2002), making fishes excellent model systems for engineers interested in improving maneuverability and stability in current aquatic and aerial vehicles. Despite the biomimetic potential of fishes, few studies focusing on stability or maneuverability have been performed, and in these areas of research, there are presently no standard techniques and approaches for measuring fundamental performance characteristics in fishes

under controlled, reproducible experimental conditions (Webb 2006). There is a particular paucity of fish stability performance studies. Eidiotis *et al* (2003) did successfully measure corrective ability of three fishes when weights were added to induce rolling instability, and Webb (1998) and Liao *et al* (2003) examined position holding, posture stabilization and/or body kinematics in fish swimming behind cylinders that produced vortex shedding. However, the difficulties associated with inducing stability control responses in live fishes have limited additional measures of fish stability performance.

Using a model-based approach involving interrelated pressure, force/moment and digital particle image velocimetry (DPIV) experiments, Bartol *et al* (2002, 2003, 2005) examined some aspects of stability control in the marine boxfishes (Teleostei: Ostraciidae), a unique group of rigid-bodied swimmers. These studies, which were performed on four morphologically distinct species of boxfishes, revealed that the keels and other characteristics of the boxfish carapace control vorticity and produce flows and pressure distributions that lead to self-correcting forces for pitch and yaw. In all four boxfishes, the ventro-lateral keels produce leading edge vortices (LEVs) that increase in magnitude when the carapace pitches and yaws at greater angles. In some species, such as the spotted boxfish *Ostracion meleagris*, the dorsal keels produce similar flows. These ventral and dorsal vortices are strongest at posterior regions of the carapace and produce self-correcting forces that presumably aid tropical boxfishes in maintaining smooth swimming trajectories in turbulent environments (Bartol *et al* 2002, 2003, 2005). Although most fishes rely heavily on sensory-motor regulatory pathways for stability control (Webb 2006), the keel-induced LEV self-correcting system of boxfishes acts passively and requires only 'unconscious attention' (Weihs 1993).

These stability findings have stimulated recent interest in boxfishes within the biomimetic community. The Office of Naval Research has explored applying boxfish control surfaces to the development of highly stable underwater robots (Choi 2003), and Mercedes-Benz recently unveiled a bionic concept car that is based on the contours of the boxfish carapace (Sharfman 2006). Micro underwater vehicles mimicking boxfish also are under development (Deng and Avadhanula 2005). Marine boxfishes are well suited for bioinspired design and engineering for several reasons. First, boxfishes exhibit a unique combination of high stability and maneuverability. Despite having a somewhat ungainly exterior, boxfishes exhibit some of the lowest amplitude recoil movements during swimming detected in any fish (Hove *et al* 2001), which is at least partly a product of the self-correcting mechanism described above, and have the ability to spin around with minimal turning radius and hold precise control of their positions and orientations (Walker 2000). Second, boxfishes have a rigid carapace encasing a significant portion of their bodies, requiring them to swim predominantly using coordinated movements of their five fins (Gordon *et al* 2001, Hove *et al* 2001) rather than relying heavily on undulatory body movements like most fishes (see Lauder and Tytell 2006). The rigid morphology of the boxfish is more directly transferable to human-designed vehicles than the deformable,

flexible morphologies of most fishes. Third, some species have large cross-sectional areas with surprisingly low drag coefficients ($C_D < 0.1$) (Bartol *et al* 2005). A large cross-sectional area coupled with low drag lends itself well to vehicle designs that require significant payload capacity.

While the keel-induced, LEV, self-correcting mechanism has been examined in model boxfishes and has generated widespread interest within biomimetic circles, self-correcting spiral flows have yet to be documented and studied in live, actively swimming boxfishes, which have greater levels of complexity than the more simplified models. Unlike models, live fishes produce respiratory flows, employ fin motions, have mucus along their bodies and are not fixed in place with a sting. Consequently, the observed self-correcting spiral flows around models may be significantly modified in live fishes, playing only minor roles in stability control. To fully understand stability in these boxfishes, it is important to determine if the underlying body flows observed around models are present and similar in nature to those occurring in live fishes. Therefore, in this study, we compare previous data collected from models with new flow data collected around the carapaces of two actively swimming boxfishes during pitching: (1) the spotted boxfish *Ostracion meleagris*, which has a trapezoidal cross-section and (2) the smooth trunkfish *Lactophrys triqueter*, which has a triangular cross-section.

2. Methods

2.1. Animals

Five spotted boxfish *Ostracion meleagris* Shaw (total length (TL) = 9.2–12.5 cm) and two smooth trunkfish *Lactophrys triqueter* Linnaeus (TL = 8.1–8.5 cm) were shipped from a local fish supplier in Honolulu, Hawaii and the Keys Marine Lab, Long Key, FL, respectively, to Woods Hole Oceanographic Institution, Woods Hole, MA. The fishes were maintained in a flow-through seawater system at 30 psu and 20–23 °C and fed a diet of lettuce, brine shrimp and flake food. Animals were kept in captivity at least one week prior to experimentation.

2.2. Digital particle image velocimetry

Each fish was placed in a water tunnel with a $45 \times 45 \times 250$ cm³ working section (Model 504, Engineering Laboratory Design, Inc., Lake City, MN) filled with seawater (22 °C, 30 psu) set initially to a speed of 5 cm s⁻¹. After at least 45 min of acclimation to the water tunnel, flow was increased in 2–5 cm s⁻¹ stepwise speed increments, each lasting 15 min, until the fish was unable to maintain position against free-stream flow. At each speed increment, we used DPIV to examine flows around the carapace, a technique for flow field measurements described in Willert and Gharib (1991) and Raffel *et al* (1998).

During experimental runs, the water tunnel was seeded with 14 μm hollow glass spheres (Potter Industries, Inc., Valley Forge, PA, USA). These particles were illuminated in a 1 mm thick parasagittal plane using two (A and B) pulsed ND:YAG lasers (wavelength = 532 nm, power rating

90 mJ/pulse; New Wave Research, Inc., Fremont, CA, USA) equipped with light-sheet optics (Dantec Dynamics, Skovlunde, Denmark) and positioned beside the working section of the tunnel. A Kodak MegaPlus model ES-1.0 (992 × 1008 pixel frame size, 30 Hz frame rate) with a 17–35 mm Nikkor zoom lens was positioned downstream of the working section to record oncoming flows. A Multicam CCD camera (992 × 1008 pixel frame size, 30 Hz frame rate) was positioned next to the lasers beside the working section to record lateral views of the swimming fishes. Although the laser and camera were mounted to a rail system capable of three-axis motion, the downstream camera was fixed and thus side camera/laser movements were confined to the region of focus of the downstream camera. Synchronization of the laser and cameras was achieved using a DG535 4-channel digital delay/pulse generator (Stanford Research Systems, Inc., Sunnyvale, CA). Each laser was triggered to operate at 15 Hz (4 ns pulse width) with a 4 ms separation between laser A and B pulses. Consequently, the time step between image pairs (ΔT) was 4 ms, and image pairs were collected at 15 Hz for up to 2 min (1800 image pairs).

Given that the objective of this study was to examine flows during pitch events, only those sequences in which the boxfish pitched at an angle $>5^\circ$ in either the positive or negative direction were considered for analysis. Pitch angle, defined as the angle between free-stream flow and a longitudinal line drawn from the bridge of the boxfish snout to its caudal peduncle, was measured using the National Institute of Health's public domain program ImageJ (<http://rsb.info.nih.gov/ij/>). For image sequences with pitch angles exceeding 5° in the positive or negative direction, bright outlines of the boxfish were first removed from the particle field using NI Vision software (National Instruments, Inc., Austin, TX, USA) to eliminate the possibility of body reflections interfering with processing routines. The images then were subdivided into a matrix of 32^2 pixel interrogation windows. Using a 16 pixel offset (50% overlap), cross-correlation was used to determine the particle displacements within interrogation windows comprising the paired images (Willert and Gharib 1991). Outliers, defined as particle shifts that are three pixels greater than their neighbors, were removed and the data were subsequently smoothed to remove high-frequency fluctuations. Window shifting was performed followed by a second iteration of outlier removal and smoothing (Westerweel *et al* 1997). Using *PixelFlow*TM software (FG Group LLC, San Marino, CA), velocity vector and vorticity contour fields were determined. Circulation was calculated by integrating vorticity within an iso-vorticity contour of magnitude equal to 10–20% of peak vorticity. The level within the 10–20% range was set according to the noise level of the data, with the ultimate goal of using the lowest contour level consistent with the quality of the data. To compare vortex strength in models and live fishes, circulation magnitudes of vortices located near the ventral keels at the posterior region of the carapace were normalized. This was achieved by dividing peak mean circulation ($\text{cm}^2 \text{s}^{-1}$) by the product of swim speed (cm s^{-1}) and total body length (cm)

3. Results

Pitching events in which the boxfish head tilted up/down about the lateral axis at angles $>5^\circ$ were rare in *O. meleagris* and *L. triqueter*; when such events were observed, they were often very brief (<1.2 s) in duration. In *L. triqueter*, both positive and negative pitching exceeding 5° were observed, but in *O. meleagris* only significant negative pitching was observed. During positive pitching events in *L. triqueter*, vortical flows formed above the ventral keels at locations similar to those observed in previous model experiments (figure 1) (Bartol *et al* 2002, 2003, 2005). The overall shape of vortices was more irregular around live fishes than around models. Vortices shed from the dorsal and anal fins were often present at positive pitch angles.

During negative pitch events in *L. triqueter* and *O. meleagris*, vortical flows formed below the ventral keels at locations similar to those observed in previous model experiments (figures 2 and 3). Vortices shed from the dorsal fin were frequently observed, but vortices shed from the anal fin generally were not present in vorticity plots. This was in part because the laser plane was often anterior to the anal fin during negative pitching events in both fishes (figures 2(d) and (e), figures 3(d)–(f)). However, even when the laser plane was posterior to the anal fin, e.g., at the caudal peduncle, only one pair of ventral vortices was often observed (figures 2(f) and 3(g)). In *O. meleagris*, weaker regions of concentrated vorticity were detected below the dorsal keels as was the case around models.

Mean circulation (Γ_v) and mean peak vorticity ($P\omega_v$) of body-induced vortices were different for live fish and models because of the dissimilar swimming speeds, pitch angles and TLs considered in the two experiments (figures 1–3). Therefore, peak circulation values of ventral vortices near the posterior carapace edge were normalized (see methods). Normalized values of vortex strength increased linearly with angle of attack for both models and live fishes (Linear regressions: $P < 0.001$; $R^2 > 0.96$) (figure 4). The slopes for regression lines were statistically greater for live fishes than models (one tailed *t*-tests: $t = 21.79$, d.f.(v) = 7, $P < 0.001$ (smooth trunkfish); $t = 5.02$, d.f.(v) = 6, $P < 0.001$ (spotted boxfish) (Zar 1996).

4. Discussion

This study provides the first evidence that the self-correcting flows observed around carapace models in previous experiments also occur in actively swimming boxfishes. At positive and negative pitch angles, prominent vortices formed above and below the ventral keels, respectively, and vortex strength increased with more positive and more negative pitch angles. These findings are important because they confirm that pressure, force/moment and flow measurements from model-based experiments (see Bartol *et al* (2002, 2003, 2005)) are highly relevant for live fishes despite important differences between the two systems. The observed infrequency of significant pitching events in this study together with the short duration of each pitching event is also consistent with previous

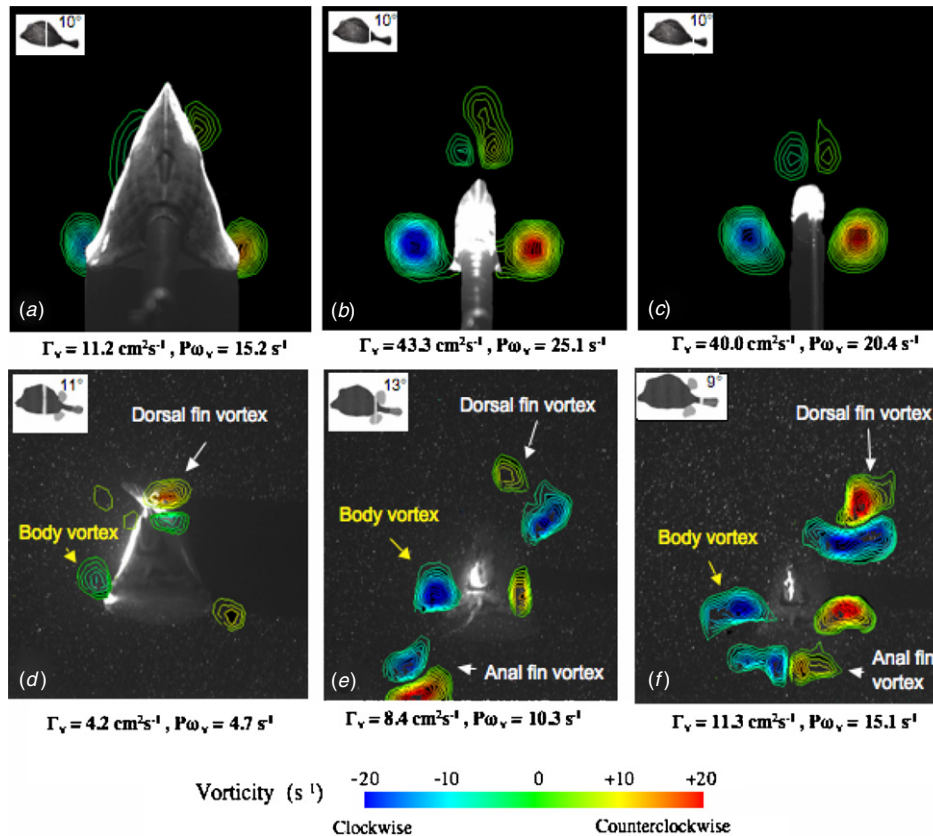


Figure 1. Vorticity contour fields around models (TL = 17.0 cm; flow speed = 44 $cm s^{-1}$) (a)–(c) and live (TL = 8.5 cm; swimming speed = 10 $cm s^{-1}$) (d)–(f) smooth trunkfish *Lactophrys triqueter* during nose-up (positive) pitching. The insets within each figure illustrate the pitch angle and location of the laser sheet. Mean circulation magnitude (Γ_v) and mean peak vorticity ($P\omega_v$) for a ventral body-induced vortex are included underneath the vorticity contour plots.

studies that demonstrate that recoil motions in boxfishes are among the lowest detected in any group of fishes (Hove *et al* 2001).

The mechanism of stability control examined in this study is unique among fishes. Most fishes rely predominantly on powered stability control, whereby propulsors are actively moved independently of the motion of the body to damp and correct for disturbances (Weihs 1993, Webb 2000, 2002). Like other fishes, boxfishes also employ powered stability control; they use properly phased short-based median and paired fin motions to reduce recoil in all directions, helping them swim in remarkably smooth swimming trajectories (Gordon *et al* 2001, Hove *et al* 2001). However, boxfishes also employ an underlying ‘passive’ self-correcting control mechanism, whereby flow is directed and controlled over the body keels and contours to produce counter moments for pitching and yawing. Although ‘passive’ induction of flows over control surfaces that move with the body for stability control is common in fishes (e.g., fins positioned at a specific attitude relative to the body) (Webb, 2000), few rely on a vortex generator mechanism quite like that found in boxfishes, though there is growing evidence that many other swimming organisms use keel-like structures as microvorticity generators (Gordon *et al* 2007). In boxfishes, the keels produce LEVs that grow in circulation

along the body, reaching maximum circulation posterior to the center of mass at the posterior-most regions of the carapace. These spiral vortices, which resemble LEVs produced around delta-winged aircraft, form above and below body keels at positive and negative pitch angles, respectively, growing in circulation strength as pitch angles deviate farther from 0°. The resulting surface pressures produced by the flows contribute to integrated forces that self-correct for pitching motions (Bartol *et al* 2003, 2005).

The keel-induced self-correcting mechanism of boxfishes has several benefits. First, it acts quickly without the need for neural processing. This is especially advantageous for the unpredictable turbulent waters in which these fishes reside, where accurate phasing of powered correction forces with perturbations is difficult and requires rapid neural processing. Powered stability control requires coordination of sensory, neural and musculo-skeletal systems, and consequently correction responses have latencies. If the response latency between sensing a perturbation and the motor response approaches half that of the perturbation period, corrective actions may amplify the disturbance in a phenomenon known as ‘pilot-induced error’ (Webb 2000, 2002). Second, the self-correcting system of boxfishes has the potential for significant energy savings over powered control systems in highly

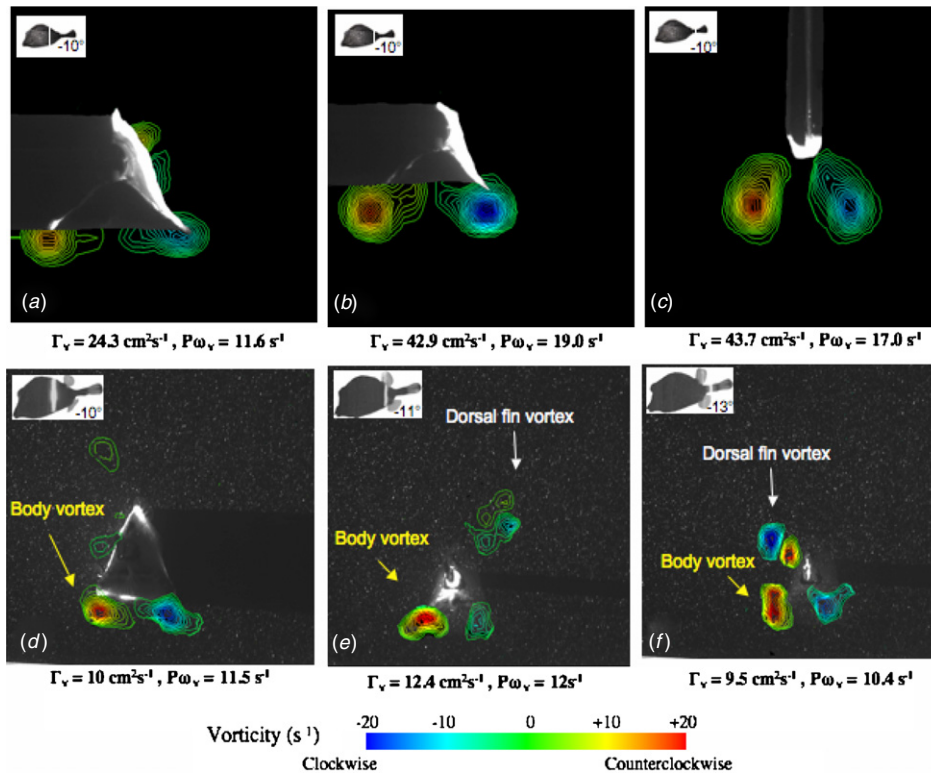


Figure 2. Vorticity contour fields around models (TL = 17.0 cm; flow speed = 44 cm s⁻¹) (a)–(c) and live (TL = 8.5 cm; swimming speed = 10 cm s⁻¹) (d)–(f) smooth trunkfish *Lactophrys triqueter* during nose-down (negative) pitching. The insets within each figure illustrate the pitch angle and location of the laser sheet. Mean circulation magnitude (Γ_v) and mean peak vorticity ($P\omega_v$) for a ventral body-induced vortex are included underneath the vorticity contour plots.

energetic turbulent waters where flows may move boxfishes unpredictably off their desired paths or positions, requiring frequent stability corrections. Third, a self-correcting system reduces complexity of movement relative to powered systems, which can enhance sensory perception (Land 1999, Kramer and McLaughlin 2001). The evolution of such a sophisticated self-correcting system in boxfishes is integral to their success within their highly variable, turbulent habitats.

One important finding of this study is that the self-correcting, keel-induced LEVs do not necessarily act in isolation and can be modified with powered input from the fins. This is apparent from the observed higher regression slopes (vortex strength versus angle of attack) in live fishes versus models. The dorsal and anal fins are not involved in circulation augmentation, at least for regions anterior to the posterior carapace edge. Vortices produced by the dorsal fin at all pitch angles and anal fin at positive pitch angles were clearly visible and spatially separated from keel-induced ventral spiral flows, irrespective of fish species. Moreover, the longitudinal sections considered along the carapace at negative pitch angles in this study were anterior to the anal fin, and thus unaffected by anal fin motions. Posterior to the anal fin, near the posterior-most edge of the carapace, our current data set is too incomplete to sufficiently assess body/anal fin vortex interaction during negative pitch events. However, merging of vorticity shed from the anal fin and body, which is common in

other fishes (see Lauder and Tytell 2006), is likely downstream of the carapace posterior edge based on the close proximity of the respective vortices and the observed vorticity patterns at the caudal peduncle.

The pectoral fins are the most likely mechanism of circulation augmentation along the carapace. The pectoral fins were active during pitch sequences in both smooth trunkfish and spotted boxfish and are positioned upstream of the keel-induced flows, directly in the path of developing body-induced spiral flows. Therefore, pectoral fin motions have an impact on ventral spiral flows, which is important for two reasons. First, pectoral fin motions can presumably supplement the underlying passive self-correcting control mechanism with powered control when needed for greater stability control. This is supported by the observed increase in regression slopes in live fishes with pectoral fins versus models without active pectoral fins. Based on the linear relationship between vortex strength and angle of attack, the pectoral fins appear to be capable of injecting vorticity in proportion to the level of trim control required. Second, the pectoral fins have the potential to generate circulatory forces of significant strength to cancel out vortices developing around the keels. This is again apparent from the regression slope magnitudes; the regression slopes of live fishes were almost twice of those detected in models, suggesting that the pectoral fins are capable of producing vorticity of similar magnitude to that produced by the keels.

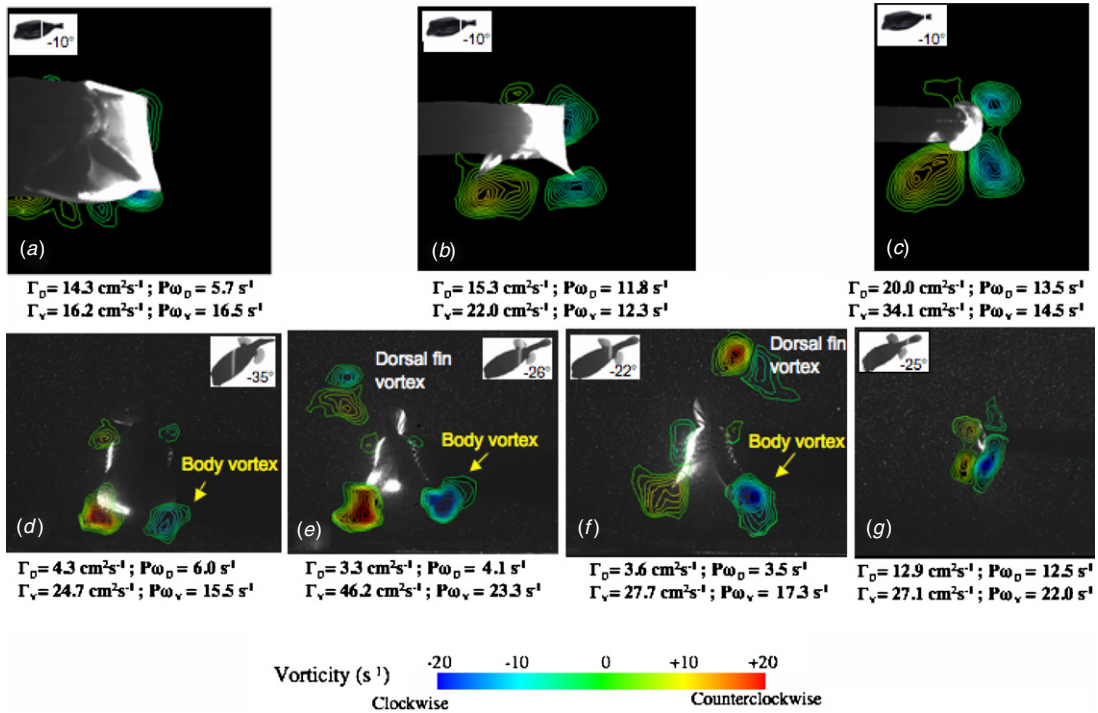


Figure 3. Vorticity contour fields around models (TL = 12.1 cm; flow speed = 44 cm s^{-1}) (a)–(c) and live (TL = 12.5 cm; swimming speed = 12 cm s^{-1}) (d, f); TL = 11.5 cm, swimming speed = 12 cm s^{-1} (e, g) Hawaiian spotted boxfish *Ostracion meleagris* during nose-down (negative) pitching. The insets within each figure illustrate the pitch angle and location of the laser sheet. Mean circulation magnitude and mean peak vorticity for a dorsal body-induced vortex (Γ_D and $P\omega_D$, respectively) and a ventral body-induced vortex (Γ_V and $P\omega_V$, respectively) are included underneath the vorticity contour plots.

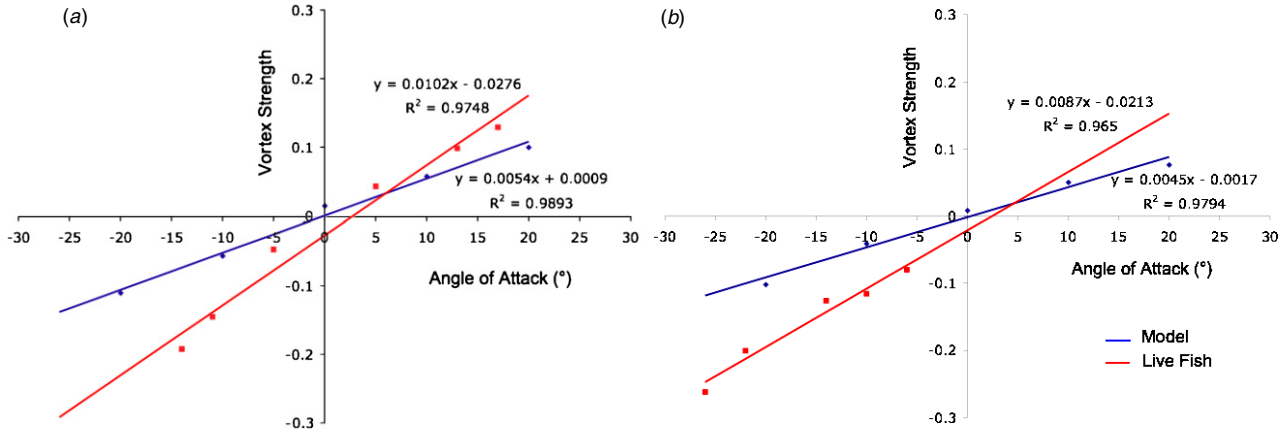


Figure 4. Vortex strength (y-axis) versus angle of attack (x-axis) for smooth trunkfish *Lactophrys triqueter* (a) and Hawaiian spotted boxfish *Ostracion meleagris* (b). Blue and red lines represent measurements collected near the posterior carapace edge of models and live fishes, respectively. Vortex strength is a dimensionless index calculated by dividing peak mean circulation for a ventral vortex ($\text{cm}^2 \text{ s}^{-1}$) by the product of swim speed (cm s^{-1}) and total body length (cm).

The ability to cancel out body-induced vorticity on one side of the fish while augmenting body-induced vorticity on the other side may be an important mechanism for achieving high maneuverability in yaw or roll when required in these fishes. Moreover, symmetric powered vorticity production may be effective in pitch when the passive keel-induced stability needs to be overruled. Given that the opercular openings of boxfishes

are immediately in front of the pectoral fin bases, respiratory flows may also be involved in the vorticity strengthening effects of pectoral fin movements.

Having a mechanism for modification of the self-correcting system is not surprising given that boxfishes are capable of maintaining pitch and yaw angles and are highly maneuverable within their natural reef environments.

Although unknown at this stage, it is conceivable that the powered and passive contributions to stability control change depending on environmental conditions, with perhaps greater reliance on self-correcting keel-induced control as pilot-induced error becomes more problematic. As mentioned above, pectoral fin movements coupled potentially with respiratory flow injections seem to be the most probable method of augmenting/bypassing the self-correcting system. However, clearly more research is needed to corroborate this and fully understand the complex vortex-wake interactions between body-induced vorticity and pectoral fin/respiratory flow vorticity. Unfortunately, conventional planar, stereo and even scanning DPIV lack sufficient spatial resolution to fully visualize and quantify these complex 3D flow interactions, which generally involve looping and interconnecting vortex streams. Consequently, more powerful 3D approaches, such as defocusing digital particle image velocimetry (Pereira and Gharib 2002, 2004, Pereira *et al* 2006) that provides volumetric, 3-component velocity field data, are necessary to fully understand the interdependence of these powered and passive systems. As stressed by Lauder and Tytell (2006), these flow quantification approaches should be coupled with high-speed, high-resolution videography for accurate kinematic records of body and fin motions. The technical challenges of using these approaches and the difficulties associated with eliciting reliable stability control responses and maneuvers in fishes are not trivial, but this research is worth pursuing given the potential benefits it holds for understanding this unique, biomimetically relevant system.

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