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HYDRODYNAMIC IMAGING BY BLIND MEXICAN CAVE FISH

Shane Windsor

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for the degree of Doctor of Philosophy,
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ABSTRACT

Blind Mexican cave fish (*Astyanax fasciatus*) lack a functioning visual system, and are known to use self-generated water motion to sense their surroundings; an ability termed hydrodynamic imaging. Nearby objects distort the flow field created by the motion of the fish. These flow distortions are sensed by the mechanosensory lateral line. Little is known about the fluid mechanics involved in hydrodynamic imaging, or how the behaviour of the fish might influence their ability to sense the world around them.

Automated image analysis was used to study the effects of swimming kinematics on the ability of the fish to sense their surroundings when introduced into a novel environment. The fish reacted to avoid head-on collisions with a wall at a remarkably short mean distance of 4.0 ± 0.2 mm. The ability of the fish to react, was dependent on whether they were beating their tail as they approached the wall. When following surfaces, such as a wall, the fish changed their swimming kinematics significantly and used both tactile and hydrodynamic information. Measuring the tendency of the fish to follow a tightening curve showed the fish to be moderately thigmotactic.

The flow fields around freely swimming fish were experimentally measured using Particle Image Velocimetry (PIV). A new algorithm was developed to calculate the pressure field around the fish based on the velocity field measured using PIV. The algorithm was validated against analytical and computational fluid dynamic (CFD) solutions.

The flow fields around gliding fish and the stimuli to the lateral line of the fish were calculated using CFD models, validated against the experimental PIV data. The flow fields changed in characteristic ways as the fish approached a wall head-on or swam parallel to a wall. At 0.10 body lengths from a wall, the stimulus to the lateral line was estimated to be sufficient for the fish to be able to detect the wall, but this decreased rapidly with increasing distance from the wall. The CFD models suggested that the velocity of the fish does not affect the distance at which they detect an object.

Hydrodynamic imaging is a short range sensory ability and blind cave fish require their sensitive lateral line and fast reactions in order to be able to use it to sense the world around them and avoid collisions. The information gained about the fluid mechanics of hydrodynamic imaging, and the flow measurement and modelling techniques developed here will be useful for further study of this remarkable ability.

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NOMENCLATURE & ABBREVIATIONS

The following abbreviations are used in this thesis:

| | |
|--------|--|
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| BL | Fish body length |
| CFD | Computational Fluid Dynamics |
| CMOS | Complementary Metal-Oxide-Semiconductor |
| fps | frames per second |
| GCI | Grid Convergence Index |
| IBC | Inside Boundary Condition |
| LED | Light Emitting Diode |
| OBC | One sided Boundary Condition |
| PIV | Particle Image Velocimetry |
| QUICK | Quadratic Upstream Interpolation for Convective Kinematics |
| RMS | Root Mean Square |
| s.e.m. | standard error of the mean |
| SIMPLE | Semi Implicit Method for Pressure Linked Equations |

The following symbols are used in this thesis:

| | |
|--------------|---|
| C_D | Drag coefficient |
| C_F | Skin friction coefficient |
| C_L | Lift coefficient |
| C_P | Coefficient of pressure |
| ΔC_P | Difference in the coefficient of pressure between canal pores |
| Cr | Courant number |
| d | Distance between the wall and the fish (mm) |

| | |
|--------------------|---|
| D | Fish width (mm) |
| f | Frequency (Hz) |
| \mathbf{f} | Body forces such as gravity (N) |
| h_{plate} | Distance from the middle of the flow to each plate (m) |
| Δh | Angle between the velocity vector of the fish and the tangent of the wall |
| L | Total length of the fish (mm) |
| Δl | Length of element |
| n | Direction normal to a boundary |
| N | Number of fish |
| p | Pressure, measured as deviation from hydrostatic pressure (Pa) |
| p_{ij} | Pressure at node number i in x direction and j in y direction |
| p_0 | Hydrostatic pressure (Pa) |
| p_{ref} | Reference pressure (Pa) |
| p_{stag} | Stagnation pressure (Pa) |
| r | Radius of curved wall (m) |
| Re | Reynolds number |
| S | Surface location on body (BL) |
| St | Strouhal number |
| t | Time (s) |
| Δt | Time step |
| \mathbf{u} | Velocity vector with components (u, v, w) (m s^{-1}) |
| \mathbf{u}_0 | Velocity field corrected for divergence |
| \mathbf{u}_{set} | Prescribed velocity at a boundary |
| U_0 | Velocity of the free stream (m s^{-1}) |

| | |
|----------------------|--|
| U_{norm} | Normalised velocity |
| \mathbf{v} | Velocity of the fish (mm s^{-1}) |
| $\Delta x, \Delta y$ | Distance between two nodes in x direction and y direction respectively |
| α | Tail angle of fish (degrees) |
| γ | Angular coordinate measured anticlockwise from the x-axis (radians) |
| θ | Angle of the fish relative to the wall (degrees) |
| λ | Correction field for divergence correction of velocity field |
| ν | Kinematic viscosity of fluid ($\text{m}^2 \text{s}^{-1}$) |
| ρ | Density of fluid (kg m^{-3}) |
| μ | Dynamic viscosity of fluid (N s m^{-2}) |
| τ | Shear stress (Pa) |
| ∇ | Gradient operator |
| $\nabla \cdot$ | Divergence operator |
| ∇^2 | Laplacean operator |

CHAPTER 1: Blind Cave Fish and Hydrodynamic Imaging

1.1 Chapter Summary

The hypogean form of *Astyanax fasciatus*, commonly known as the blind Mexican cave fish is found in subterranean caves in Mexico. As these fish lack eyes they have prompted researchers to investigate how they manage to move about their environment without a visual system. It has been found that they use hydrodynamic imaging, whereby the fish detect their surroundings by sensing distortions in the flow field created by their own swimming motion. Cave fish can then use this to build up a cognitive map of their surroundings. It appears that cave fish can also actively enhance their ability to sense their surroundings by increasing their swimming speed.

A. fasciatus use their lateral line to measure the flow field around them. The lateral line is a mechanosensory system found in fish which is composed of haircell based sense organs known as neuromasts which make up two sensory subsystems. The superficial neuromasts are on the surface of the skin and encode largely velocity information. The canal neuromasts are located in canals under the skin surface with pores opening to the surrounding fluid and primarily encode pressure gradient information. The lateral line system of the hypogean form of *A. fasciatus* is typical of many teleost fish, except that there are a large number of superficial neuromasts. This is not dissimilar to the numbers of neuromasts found in some closely related non-cave species. It has been found that the cupula of the superficial neuromasts of the cave fish are longer than those of the sighted river population of the same species, which may serve to increase their sensitivity to flow. The relationship of this observation to hydrodynamic imaging is unclear since it has been demonstrated that the canal system (rather than the superficial system) is principally involved in this behaviour. Overall, we know that blind cave fish use their lateral line to gain information about their surroundings and we have a general idea as to how this might work using hydrodynamic imaging. But we do not have a good understanding of the flow field around the fish and how this is altered by external objects or by changes in the fish's swimming behaviour. How these factors influence the fish's ability to sense the world around them using hydrodynamic imaging is an open question.

1.2 Structure of Chapter

This chapter introduces blind cave fish and the research that has been conducted into their ability to sense their surroundings using hydrodynamic imaging. The structure and properties of the lateral line system are also reviewed.

The chapter is arranged in the following structure:

1.3 Blind Cave Fish

Introduces blind Mexican cave fish and briefly overviews the habitat where they are found.

1.4 Hydrodynamic Imaging

Describes hydrodynamic imaging and what is known about it.

1.5 The Lateral Line

Reviews the morphology and function of the lateral line.

1.6 The Lateral Line of Blind Cave Fish

Reviews what is known about the lateral line of blind cave fish.

1.7 Conclusions

Summarises the conclusions that can be drawn from this chapter.