Proper Orthogonal Decomposition and Particle Image Velocimetry in Bat Flight

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We present an interactive visualization and exploration tool for displaying and analyzing complex kinematic motion of a bat wing in flight, combined with the slices of vorticity in the wake flow obtained with particle image velocimetry (PIV). The system was designed to help animal-flight experts study the biomechanics of bat flight.

1 Introduction

The only flying mammal, the bat (*Chiroptera*) is extremely maneuverable and utilizes energy efficient flight strategies. Flexible wing frame construction and extensible membranes are among the features unique to bats that make their unsteady flight patterns possible.

Correct models of complex flight, such as bat flight, have the potential to foster significant new discoveries in the biological evolution of flight. These models may also provide insight useful for engineering flight vehicles with increased maneuverability and in-flight sensing capabilities. To construct these models, one needs to understand and represent both the complex motion of bat wings in flight and the associated aerodynamic forces and behaviour of fluid flow surrounding the flying animal.

In our work we present an exploration tool that would allow researchers to display this surrounding flow in conjunction with bat kinematics information.

2 Methods

2.1 Data Acquisition

Three-dimensional bat wing kinematics data is collected using high-speed (f=500Hz) infrared cameras that capture the positions of reflective markers attached to bone joints and wing membranes. PIV cameras (f=5Hz) capture imagery of micron-sized particles in the wake behind the flying bat, and this imagery is used to compute slices of 2D velocity vectors and a derived vorticity field.

2.2 Proper Orthogonal Decomposition

Proper Orthogonal Decomposition (POD) is a well-known technique for analyzing multidimensional data. This method essentially extracts the dominant features in space and time. It provides an orthonormal basis for representing given data, which is optimal in a least squares sense [3]. The basis is completely data dependent and no a priori assumptions of the data structure is needed. By truncating the POD basis the optimal lower dimensional approximation of the data can be found, which allows us to study the wing kinematics data in terms of a significantly reduced number of motion components. For a detailed description of biological applications of the POD method, we refer to [1, 5].

2.3 Particle Image Velocimetry

The importance of relationships between wing geometry and simulated fluid flow around the bat is discussed in [2, 6]. A key to studying these relationships is the vorticity field around the wing, especially in the wingtip regions. Previous studies of bird flight [7] have shown that the PIV method – which provides experimental measurements of instantaneous velocity vector data in a cross-section of the flow – is an effective way of determining power, forces, and vorticities, as well as describing wake structures in general. The advantage of using PIV is the collection of experimental data, which allows us to study the real flow instead of an output from a simulator. Recent work by Lauder and Drucker [4] outlined PIV techniques used to analyze wakes behind the fins of a moving fish, which is a case similar to visualizing PIV slices in the wake behind a flying bat.

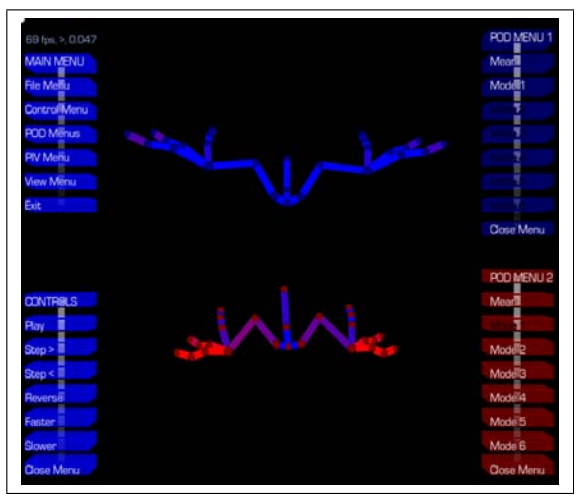

Figure 1: (in color) Two models are animated based on the different combinations of the POD components. The wing bones are colored based on the variation of their length due to the deformation during the wing motion. The wing membrane is not shown.

2.4 Visualization of Kinematics and PIV data

Our visualization tool produces a three-dimensional motion of the bones and the membranes of the wings of two bat models from the

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pre-computed POD decompositions (see Fig. 1) and combines these data with the PIV slices. From the vorticity field, a texture is generated for each PIV slice and registered to an appropriate time and position in kinematics data. A common usage of this feature by bat flight researchers involves displaying a simple mesh of markers attached to bat wings and simultaneously looking at the corresponding vorticity field (see Fig. 2), which helps to visually establish a connection between the motion of the wing in the wingbeat cycle and the vortices that are produced by this motion.

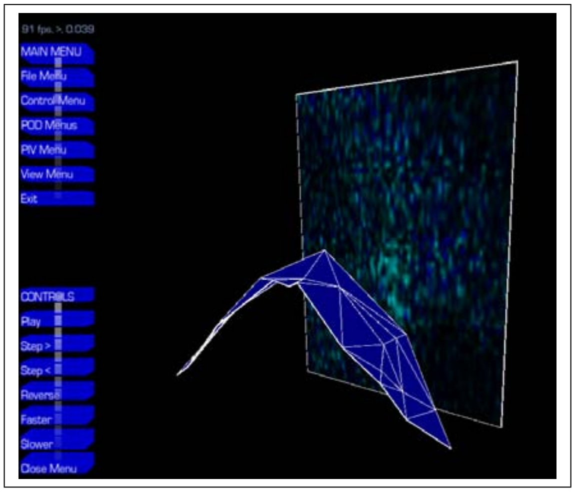

Figure 2: (in color) Simultaneous visualization of the wing membrane kinematics and a slice of the vorticity field in the wake behind the bat.

2.5 Visualization Control

The user interface consists of a keyboard and a mouse, or, alternatively, of a head tracker and a finger tracker in a Fish Tank virtual reality environment [8]. The user can access the menu, grab the models, rotate them and place each of them in a preferred location in space. The menu provides convenient access to timestepping and speed controls, which are essential for effective and thorough control of the animation. Using the menu, the user can interactively explore the contributions of individual POD components, as well as different combinations of components.

3 Conclusion

The application, developed in close collaboration with the bat flight research group at Brown, was tailored to meet the joint efforts and needs in visualizing the data acquired during the experimental test runs. The visualization system was evaluated by scientific users and received positive feedback. The biologists appreciated that the complex three-dimensional motion of the wings was represented as a linear combination of simpler motions described by the POD components. Results of preliminary studies show that the POD basis is consistent between bats of different species, and some of the POD components have an intuitive biological interpretation [5]. Meanwhile, simultaneous display of kinematics and PIV slices provided a new way to look at the wing motion and vorticity of the flow around the animal. The tool has already helped the group uncover calibration errors present in the digitized data, and will continue to be used in visualization and validation of captured datasets throughout the next several years.

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Interactive visualization and exploration system for motion and flow data

- Used by animal-flight experts to study the biomechanics of bat flight
- Display of complex kinematic motion of a wing in flight
- Pattern analysis using the optimal lower dimensional approximation
- Visualization of vorticity in the wake: cross-sectional slices of real flow

Overview

The only flying mammals, bats (Order Chiroptera) are extremely maneuverable and employ energetically efficient flight strategies. Flexible wing frame construction and extensible membranes are among the features unique to bats that make their unsteady flight patterns possible.

Our visualization tool displays the three-dimensional motion of the bones and the membranes of the wings of two bat models from pre-computed POD decompositions (see Figures 3 and 4) and combines these data with the PIV slices. From the vorticity field, a texture is generated for each PIV slice and registered to an appropriate time and position in the kinematics data.

One typical way bat flight researchers use this feature is to simultaneously display an animated mesh of markers on the bat wings with the corresponding vorticity field (Figure 2). This visually connects the motion of the wing through the wingbeat cycle to the structure of the flow created by this motion.

Data Acquisition

Three-dimensional bat wing kinematics data is collected using high-speed (f=500Hz) infrared cameras that capture the positions of reflective markers attached to bone joints and wing membranes. PIV cameras (f=5Hz) capture imagery of micron-sized particles in the wake behind the flying bat, and this imagery is used to compute slices of 2D velocity vectors and a derived vorticity field.

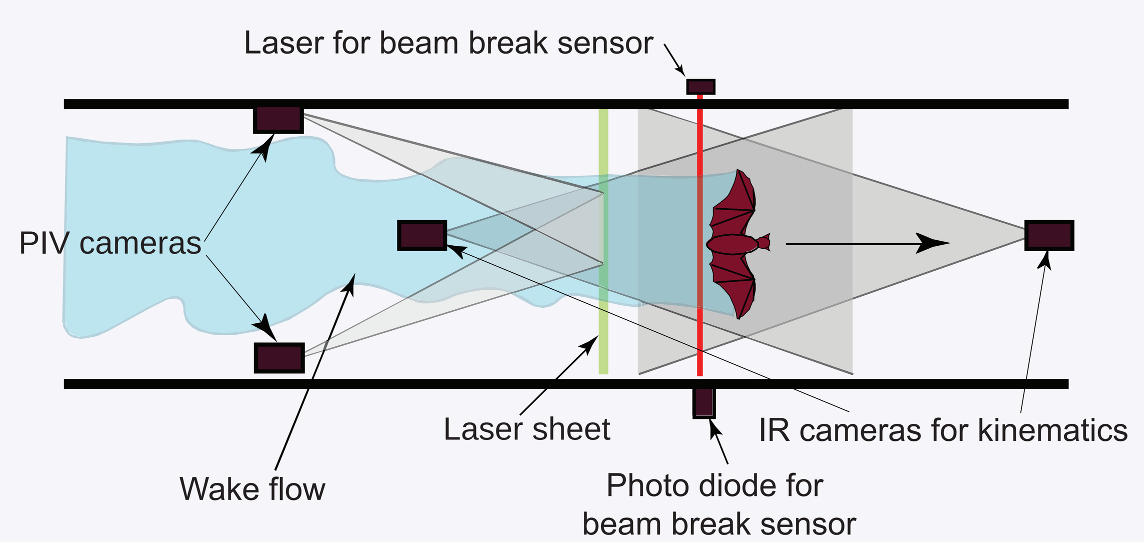

Figure 1. Experimental setup for the measurement in the transverse plane. The acquisition sequence is started when the bat triggers the beam break sensor. The flow slices of the wake are taken with the PIV camera pair.

Particle Image Velocimetry (PIV)

Experimental measurements of instantaneous velocity vector data in a cross-section of the flow

- Effective way of measuring power, forces, vorticity, and wake structures [3]
- Important for characterizing the vorticity field in the wake (especially in the regions behind wingtips)

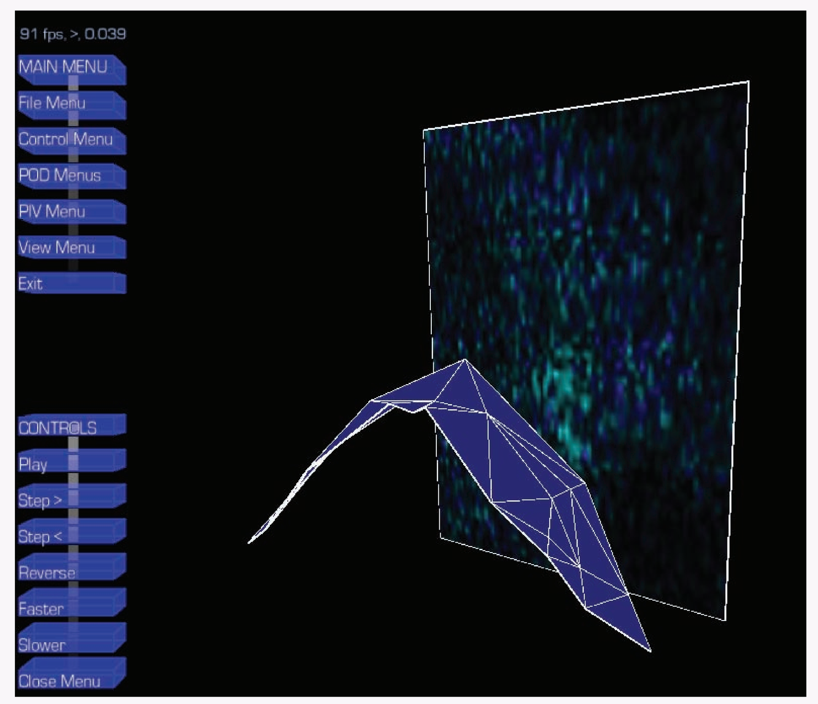

Figure 2. Simultaneous visualization of the wing membrane kinematics and a slice of the vorticity field in the wake behind the bat.

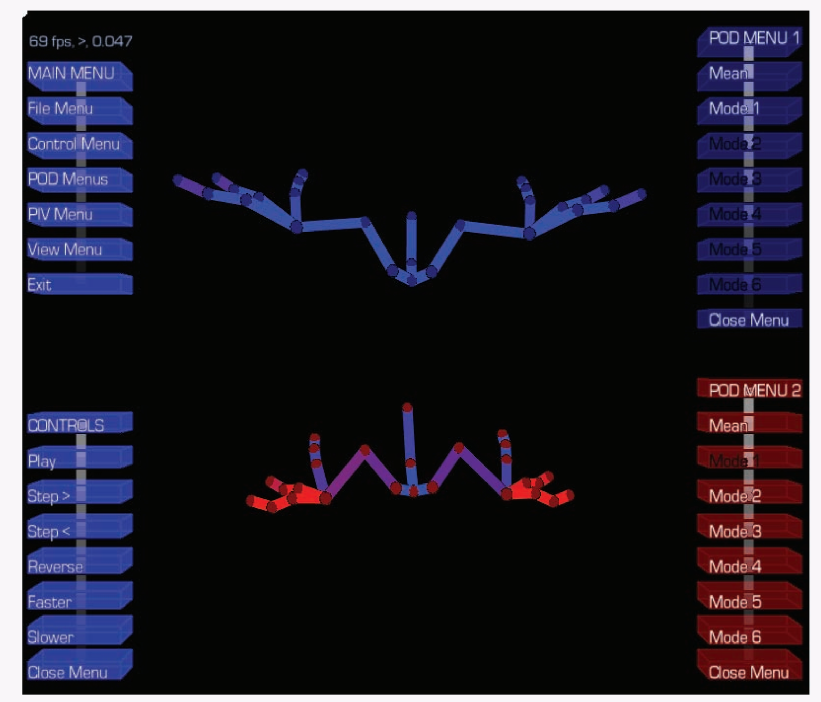

Figure 3. Two models are animated based on the different combinations of the POD components. The wing bones are colored based on the variation of their length due to the deformation during the wing motion. The wing membrane is not shown.

Proper Orthogonal Decomposition (POD)

- Extracts dominant features in space and time
- Represents given data with an orthonormal basis
  - optimal in a least squares sense [1]
- Depends completely on data
  - no a priori assumptions of data structure

Result: kinematics data is in terms of a significantly reduced number of motion components

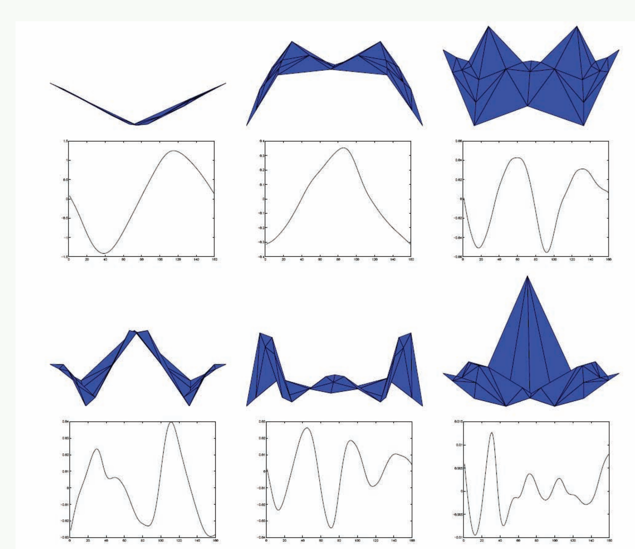

Figure 4. The geometry of the first six vertical POD modes and corresponding expansion coefficients, ordered left to right and top to bottom.

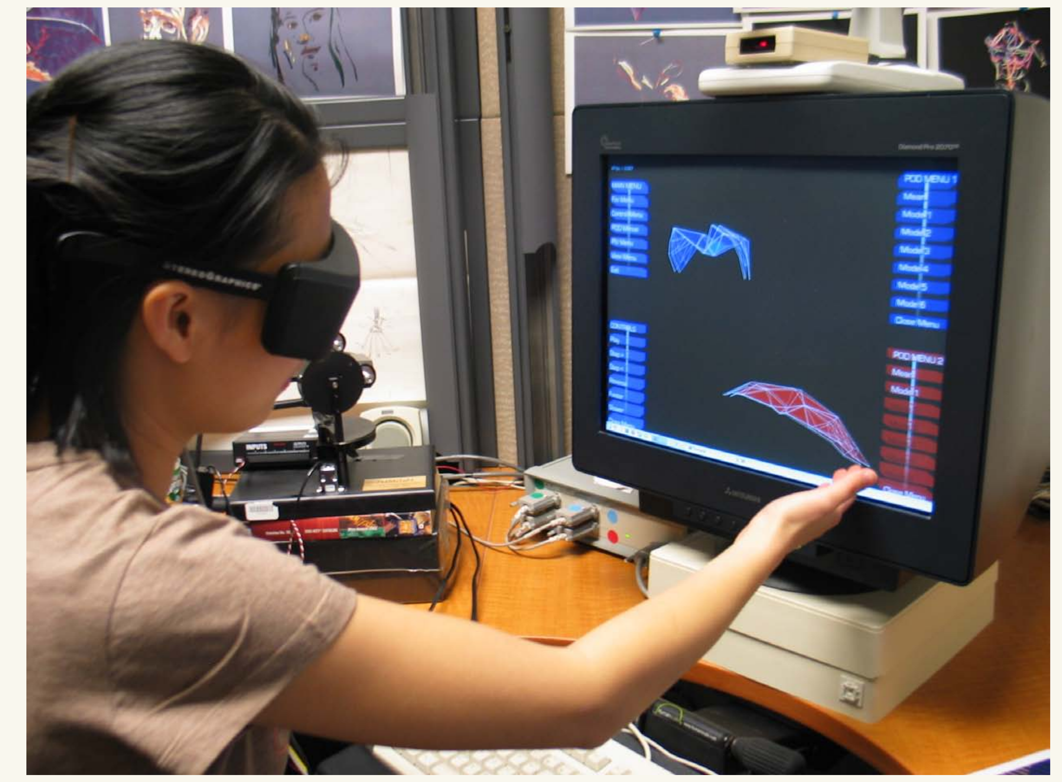

Figure 5. A user exploring a bat motion dataset in a fish tank virtual reality environment.

Visualization Control

- Desktop (keyboard and mouse) or fish tank VR (head tracker and finger tracker)
- Interaction with models and the world (move and rotate)
- Timestepping and speed controls
- Viewpoint presets (basic zoological reference planes and custom views)
- Controls for selecting active POD components

Evaluation and Results

The application was developed in close collaboration with the bat flight research group at Brown. It was tailored to meet the joint efforts and needs in visualizing the data acquired during the experimental test runs and was evaluated by scientific users. The biologists appreciated that the complex three-dimensional motion of the wings was represented as a linear combination of simpler motions described by the POD components. Results of preliminary studies show that the POD basis is consistent between bats of different species, and some of the POD components have an intuitive biological interpretation [2].
Meanwhile, simultaneous display of kinematics and PIV slices provided a new way to look at the wing motion and vorticity of the flow around the animal. The tool has already helped the group uncover calibration errors present in the digitized data, and will continue to be used in visualization and validation of captured datasets throughout the next several years.

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