Undergraduate Research Thesis

Deformation of fire ant rafts under uniform flow

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1) Abstract

Fire ants link their bodies together to build rafts. These structures help them survive floods, river flow, and rain. The ability to adapt to changing fluid environments allows fire ants to remain stable on the water surface for weeks. In this study, we record the response of fire ant rafts for 10 hours to uniform flows at 6 cm/s. We observe that raft elongation and stretching downstream are observed in the presence of flow. The deformation is caused by two factors: mechanical passive reaction and the biological active response from fire ants. To investigate these two types of responses separately, we first perform computational fluid-structure-interaction simulations of a pure elastic elliptical raft under uniform flow. The simulation results in a shape with the leading edge compressed and the aspect ratio reduced, which is different from our experimental observation. Thus, by comparing the theoretical passive response to the actual raft's behavior, we further confirmed that the responsive activity of fire ants plays a more critical role in their shape change. In addition, the streamlined shape decreases the fluid pressure by around 40% for the raft under flow. This change in external stress indicates that ants are able to sense the fluid force and make decisions to act in an opposing manner. The findings of this research may provide insights for designing an intelligent swarm robotic system with an active elongating mechanism that helps adapt to fluid flows.

2) Introduction

There is a rising trend to apply collective behavior demonstrated by animals and insects to robotics and in particular swarm robotics. The design of swarm robotics inspired by fish [1] and cockroaches [2] all incorporate these creatures' ability to react and adapt to environmental changes. Being able to deform into different shapes under the effects of wind and water, fire ants are also known for their capability to carry out complicated tasks [3] and have also helped the innovation of connection and communication of robotics [4]. Fire ants have the potential to push forward the innovation in robots that work under dangerous situations such as ocean waves and tsunamis [5] and contribute to the promising field of search and rescue of swarm robotics especially with their ability to form rafts on the water [6].

However, little is known as to how fire ants adapt their raft structures to changing environmental conditions. When biological organisms like ants may be considered as active materials. These materials are composed of self-driven units that consume or convert energy by generating mechanical stress with collective motions [7]. Therefore, the complex structure formed by the collaboration between each individual fire ant has drawn the attention of biomechanical engineers. Fire ant researchers are specifically interested in deformation and elongation, which are the typical ways that active matters dynamically react [8]. These behaviors are also statistically predicted with simulations [9] and observed when the fire ants aggregate on the water [10]. However, there are no details on how fluid forces and stress affect the entire ant colony or how they affect the actions within the colony.

To better understand how fire ant rafts dynamically respond to external forces and stress, this study focuses on investigating the fire ants' rafting mechanism under a uniform water flow. Section 3 begins by reviewing previous studies that discuss possible reactions to natural changes in fire ant behavior. Next, we provide a comprehensive view of our experimental procedures and a comparison between the experiment and simulation model. Lastly, we flesh out the implications of our work and suggest directions for future research.

3) Literature Review

Collective behaviors are commonly observed on biological matters at different scales: fish, birds, insects, and even cells [11]. There are rising applications of collective motions in autonomous, self-assembly robotics [12] or decentralized communication between devices [13]. In the field of swarm robotics, being able to scale the number of individuals from 10 to 1000 is a critical feature [14]. However, few studies exist on the performance of a large number of swarm animals since it is difficult to acquire and control the volume of subjects needed. Therefore, insects are often used for observing swarm behavior. For example, termite-inspired robots are used for performing construction tasks under dangerous situations [15]. Due to the accessibility of the insects themselves and the availability of performing experiments in a limited time and space, this study selected fire ants as the ideal subject. We study the coordination of large fire ant swarms that are able to build rafts composed of up to 10,000 individuals.

Fire ant aggregation is a common phenomenon that can be observed while the colony works together for survival by deforming into different shapes under severe environmental disasters [16]. To not be washed away by heavy rain or flood, fire ant clumps tend to attach to vegetation or jam near rivers or lakes and start deforming into an ant tower [17]. This deformation process is found to be a trial-and-error process for fire ants to find the most stable shape that could protect them from currents or wind [18]. Fire ants demonstrate the ability to consider the cost-benefit trade-off while dynamically adjusting the properties of bridge structures under changing environmental conditions [19]. To overcome these environmental changes by self-aggregating, fire ants can balance construction costs with foraging benefits. Though the advantages and details of the tower building techniques in fire ants have been studied, there has yet been an overall dynamic observation of these techniques on rafts.

With the collective intelligence to increase the survival rate by deforming, fire ants can still survive with a special rafting technique even if they are washed into the flowing water. The waterproof raft structure allow fire ants float on water surfaces for weeks until they land [20]. Water flow is a critical external factor that will affect the rafting process and the raft's shape. This assumption is based on the general understanding of fluid dynamics and the physical properties (elastic modulus, density, and viscosity) of fire ant rafts reported by Mlot et al. [10]. Based on these reported raft features in previous studies, fire ant rafts can be classified as a viscoelastic material with the characteristics of fluid and solid[10], [21]. However, there is of yet no detailed reports on how fire ant rafts react dynamically to water flow.

The interaction between fire ant raft and water is a fluid-dynamic process and forces which exert on the raft can be reflected in the raft's shape. During the process in which fluid-like inorganic materials interact with water flow, distinct shapes are observed [22]. A mathematical model is provided to explain that the potential flow can turn long bodies into the stream and can cause spherical bodies to become streamline-shaped bodies [23]. In fact, both circular and ellipse shapes appear in the rafting process but the reason behind the formation has yet to be found [4]. On the other hand, creatures change the shape of their gathering in order to survive rapid flow or maximize the chance to predate the prey in the world of biology. Sponaugle [24] claimed that corals (gorgonians) face several design conflicts between minimizing drag forces and increasing the surface area exposed to the flow for maximal food capture, concluding that kelp also forms into a streamlined shape to reduce drag [25]. Being categorized as the self-healing material, fire ants face this same challenge of survival while rafting during a flood and it is observed that the appearance of the raft changes through time [16]. The shape that reduces the drag performance on the fire ant rafts can be predicted. Our research investigates that performance and the quantitative analysis of the scale of how living creatures deform.

4) Methods and Materials

4.1) Experiment

Fire ants (*Solenopsis Invicta*) were collected on Georgia Tech's campus in Atlanta, Georgia. The experiments were done within 2 months of collection. Ants were fed with water, honey jelly, dried crickets, and fly larvae. A 10-gallon aquarium tank containing water was utilized to mimic the floods that fire ants encounter in nature. To generate a circulating water flow, a magnetic rotor was placed in the tank. The anchor is a bolt placed in the tank serving as the object that fire ants will cling to during the flood for survival.

Experiments were done with ant balls weighing 250 mg, which contained around 200 ants. After swirling fire ants into a ball shape by placing ants in a beaker, we then dumped them onto the water surface. The ball expanded and made a raft around a bolt which prevented them from being washed downstream when the flow was applied. The balls were 0.2 cm in diameter when they first touch to water. Snapshots were taken with an HD webcam Aoni C33 for 10 hours and these images were analyzed using the image analysis package in MATLAB.

For the following analysis and quantifying raft deformation, we define two dimensionless variables to compare the response of the raft in still water and under flow:

$$L^* = \frac{L}{W}$$

$$x^* = \frac{x}{L}$$

The aspect ratio L^* is defined as the ratio between the length L and width W. The normalized displacement x^* is defined as the displacement of the centroid from the anchor along the stream direction x divided by the raft length L. The schematic of the variables is shown in Fig. 2(A).

4.2) Numerical simulation

To quantify the benefit of raft deformation and to compare the raft deformation with a passive elastic body, 3D simulations are performed by using COMSOL Multiphysics. The fluid field and the solid field are fully coupled on the deformable boundary, i.e., the raft boundary. The fluid field is assumed incompressible, and the properties of water are used.

Our research assumes a purely elastic raft would contrast the effect of the active movement of ants on the raft. The fire ant raft's Young's modulus is 200 Pa, the Poisson's ratio is 0.2, and the density is 340 kg/m [22].

To ensure the stability of the computation, we define the problem as a time-dependent study with water inflow ramping up from 0 to 6 cm/s. The flow rate is set to plateau at 6 cm/s after around t = 15 s in the simulation. The flow quickly stabilizes afterward, and no oscillatory pattern is found till the end of the simulation at t = 60 s. We report the results at the last time step.

5) Results and Discussion

5.1 Stretching and deforming under uniform flow

Our 10-hour long experiment revealed that, regardless of the flow condition, the fire ant rafts contract slowly with time. This slow contraction follows a rapid expansion which was also observed in the previous study [10]. The expansion of the 2.5g weight of the fire ant raft was only 1.5 to 2 layers of ant thickness and gradually grew to an area of $6cm^2$. The rafts contracted into a compact ball of diameter 4 cm after the span of 5 hours. To quantify the contraction, the data from the raft's area and perimeter length are extracted and presented in Fig. 2(B) and 2(C) The area plot shows that the contraction rate of the rafts under flow is similar to that on a still water surface. However, rafts on the stationary water surface have rougher boundaries, leading to slightly longer perimeters.

In addition to the contraction observed in all situations, the fire ant rafts respond to the 6 cm/s water current through stretching. The deformation is described by dimensionless variables shown in Fig. 2(D) and 2(F). The variable aspect ratio is defined as the ratio of its longest dimension L to its shortest dimension W. For raft subject to flow, the aspect ratio of the rafts L^*begins at 1. Over three to four hours, the aspect ratio increases to as large as L^* = 2~3. On the other hand, the raft when it experienced no flow has a similar initial aspect ratio but remains close to L^* = 1.5 throughout the trials.

Further, the orientation variable in Fig. 2(E) shows that rafts always orientate along with the flow in response to the water current, as $\cos(\theta) \approx 1$ throughout the trial. In contrast, the patternless $\cos(\theta)$ of rafts on still water indicates that rafts are randomly orientated. This alignment is caused by the reconstruction of the raft.

Displacements in the raft's center with respect to their original position is noticed in the experiments under fluid flow. We use the normalized displacement x^* (defined in the method section) to quantify the offset of the raft's centroid from the anchor. In still water, the center of the raft is located right on the top of the anchor, resulting in $x^* \approx 0$. Under flow, $x^*$is around 0.25, indicating that the rafts are situated downstream from the anchor by a quarter of their diameter. The fluctuation variation in x^* in the Fig. 3(F) plot is the result from the fire ant's constant movements and the deforming of the raft. Currently, we are still investigating this continuous small variation in a separate study as it is most likely caused by the collective exploration activity of the rafts.

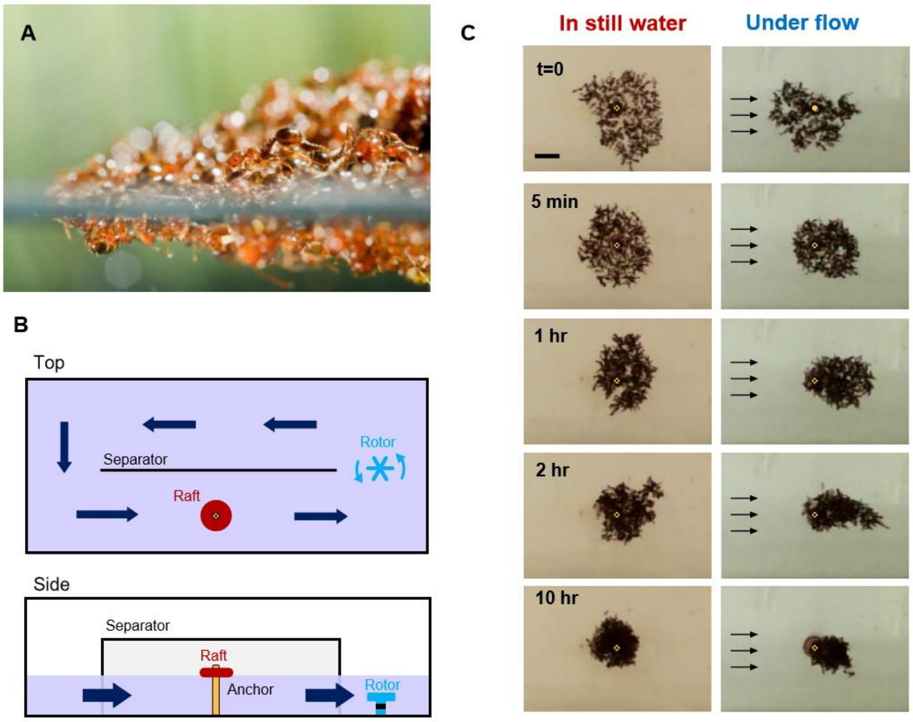

Figure 1. (A) A photo of a fire ant raft on a still water surface. (B) The experimental setup of the study. (C) Snapshots of the fire ant rafts in still water(left) and under uniform flows (right). The cross symbol in yellow represents the anchor, as in the rest of the figures.

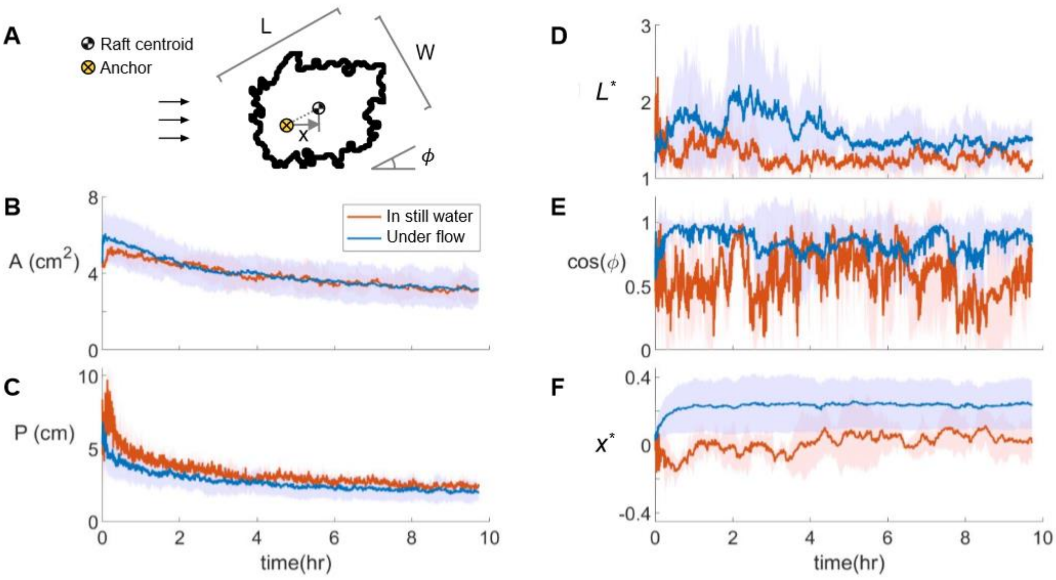

Figure 2. Raft deformation dynamics. (A) A schematic for the variables we extracted through video-processing. Time series for (B) area, (C) perimeter length, (D) aspect ratio L^*, (E) cosine of orientation θ, and (F) normalized displacement of the raft centroid x^*. The definitions of L^* and x^*can be found in the method section. Blue and red represent with and without flow, respectively. The width of the shades are 2 times the standard deviation.

5.2 Fluid-structure interaction simulations

Fig. 3(a) shows the resulting pressure distribution of the simulation with flow pasting an elastic elliptical body from right to left. Also, the colors red, yellow, and blue denote the pressure from high to low. Based on observations, the higher pressure is located near the leading edge, while the lower pressure is at the trailing edge. This pressure change could create a suction force at the trailing edge based on the Bernoulli equation. Thus, the simulation demonstrated a raft with a compressed front and a stretched middle and back under the flow situation.

The comparison of the simulated result of how a passive elastic elliptical body would deform under flow with the active response situation is demonstrated in Fig. 3(b). Using the passive body to simulate, the compression occurs in the flow direction (x direction) and the raft stretches in the traverse direction (y direction). This expansion at the middle section of the raft is due to the pressure dominating over a viscous force, which is likely to happen with our setup Reynolds number of 600. However, in the experiment, the ant raft behaves more similar to the active response in Fig. 3(b), when it maintains its width while elongating. From the discrepancy between the width change of passive and active response, it is clear that the ants are indeed reacting to the external force collectively as an active material.

Lastly, Fig. 3(c) and 3(d) which presented the structural advantages of elongating shape are quantified by demonstrating the relationship of aspect ratio with stresses. In Fig. 3(c), it is obvious that all the normal stress decreases when the raft stretches in the direction of flow. As the raft elongates to the aspect ratio of 3, the normal stress of the raft's middle and trailing section decreases by 40% ~ 60%, while the raft's leading-edge experiences a 20% loss in normal stress' magnitude. In addition, the same trend of declining stress can be found in the solid stress analysis. The solid stress drops from 9.6 to 3.6 Pa as the raft elongates to an aspect ratio of 3. This decrease in solid stress is most likely due to the reduced fluid stresses acting at the raft boundary.

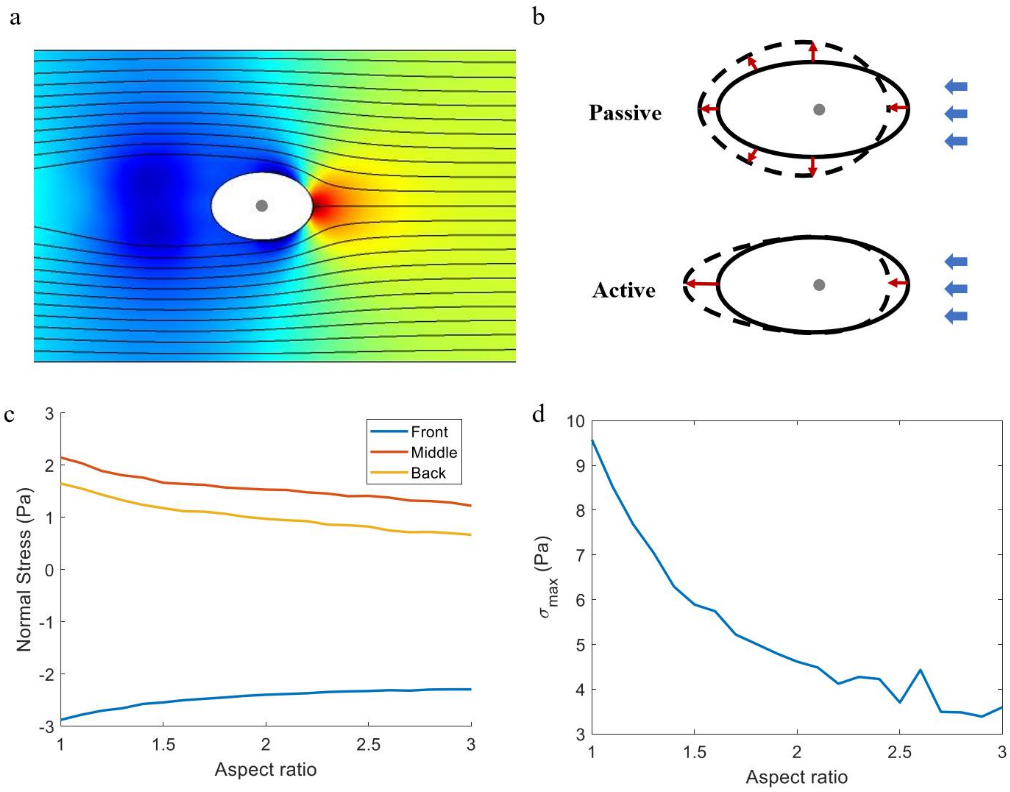

Figure 3. Simulations of a linearly elastic ant raft. (a) the streamlines and the pressure distribution of the flow velocity around an elliptical raft. Pressures cause the front end of the raft to be compressed, while the middle section and the back of the raft is stretched. (b) Schematics compare the behavior of a passive and active ant raft. The passive is the response of a linearly elastic material and the active corresponds to our observations of ants. (c - d) the relationships between aspect ratio and normal stress on the elastic raft.

6) Conclusions

In conclusion, we demonstrate through experimental approaches that fire ant rafts deforms under fluid flow. Moreover, the deformation of the ant rafts cannot be achieved with the model of a uniform elastic solid using numerical simulations. This discovery indicates that fire ants are actively responding to the water flow by stretching into a streamlined shape. Lastly, the research quantifies the hydrodynamic benefit the ant rafts obtain through streamlining. The findings of the study should provide insights into designing large robot swarms that can adapt to fluid disturbances in the wild.

7) Future Directions

This study shows the deformation of fire ant rafts under a 6cm/s flow. However, fire ants react to a faster water current in a larger group with 1000~10000 individuals in nature. Future work will involve scaling up the raft size and flow velocity for the rafting experiments. Additionally, future experiments on tracking the individual ant's trajectory moving on the raft will need to be done in order to establish a comprehensive understanding of the mechanics of the collaborative behavior of fire ant rafting. Recognizing the relationship between individual ants and fire ant aggregation can also provide better insight into designing the communication system for swarm robotics.

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