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Research on the Cavitation in the Snapping Shrimp: A Review

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Abstract: The snapping shrimp is a member of the family *Alpheidae*, which is characterized by having asymmetrical claws. When it comes to danger or when it finds prey, the snapping shrimp will close its snapping claw rapidly, generating cavitation bubbles to stun or kill the prey instantly, accompanied by huge energy. This unique biological characteristic was studied since the 1950s, mainly on three aspects, the structure of snapping claws, cavitation jet properties of snapping shrimp and the mechanism of cavitation in snapping shrimp. The article summarizes the progress and results of the research from the above three aspects, and proposes the bionic technology is the research direction of cavitation by snapping shrimps in the future, which is based on research of the biological structure of the snapping claw.

1. Introduction

Ocean resources are rich and full of potential which are important for future research. The creatures in the ocean are the treasures that nature gives to humans. After hundred millions of years of evolution, the creatures in the ocean have excellent navigation, positioning and attack abilities, which provides humans with biology models to solve problems. There is a kind of shrimp living in the tropical ocean named snapping shrimp(Fig.1). When it comes to danger or when it finds prey, the snapping shrimp will close its snapping claw rapidly, generating cavitation bubbles to stun or kill the prey instantly, the biological characteristic of which is rare to find in other creatures. The study on the mechanism of snapping cavitation and snapping claws can help to improve cavitation research and develop cavitation generator and underwater weapon. Related research mainly focused on the three aspects, the structure of snapping claws, cavitation jet properties of snapping shrimp and the mechanism of cavitation in snapping shrimp.

2. Research Process

2.1 Research on the Structure of Snapping Claw

The snapping shrimp is a member of the family Alpheidae. It is characterized by having asymmetrical claws, the larger of which can grow to 2.8cm in length, about half of its body size. The claw has a protruding plunger (pl) on the dactyl (d) and a matching socket (s) in the immobile propus (p) (Fig.2) [1]. In 1974, Roy E. Ritzmann in the Department of Biology at the University of Virginia determined the process of excitability and signal transmission in the muscles of the claw by Neuropotential stimulation on different parts of the muscle[2]. It was found that the behavior of generating jets by

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snapping shrimp was caused by the contraction of the open muscle of the claw, causing the raising state of the dactyl, followed by the excitatory of the closed muscle, and the closing behavior was done. By dissecting the small claw without jetting behavior, it was found that the small claw was more slender than the large claw, and there was no plunger or socket on the small claw compared with the large claw. However, both the large claw and the small claw had similar nerve and muscle distributions, which explained the reason that when the large claw broke accidently, the small claw would grow to the large claw and the original large claw will grow a new small one.

Fig. 1. Snapping shrimp

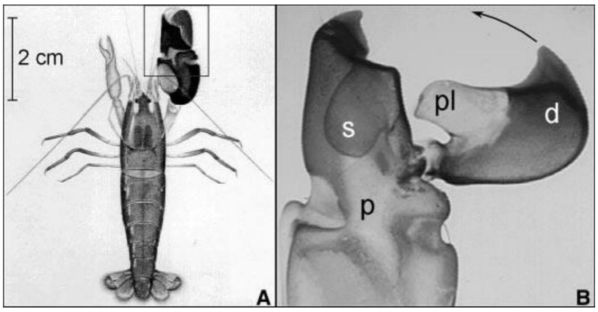

Fig. 2. the claw structure of snapping shrimp

In 2005, Arthur Anker in Department of Biological Sciences at the University of Alberta, did research on the evolution of the snapping shrimp body and claw structure[3]. In 2018, Tomonari Kaji in Department of Biological Sciences at the University of Alberta, reconstructed different movement structures of the snapping shrimp through CT scan, FESEM, high speed camera testing and 3D printing[4]. The evolution of the morphology and structure of the shrimp claws were studied in detail, as well as the movement mechanism and the joint structure of the large and small claw of the shrimp(Fig.3). By analyzing the closing speed of different joint types, it was proved that the subtle changes in the joint structure could lead to great changes in the function of the claw.

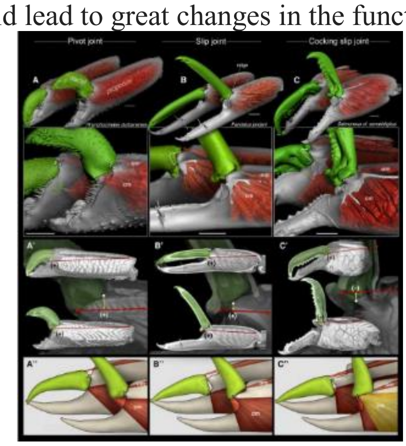

Fig. 3. Different joint types of shrimp claws

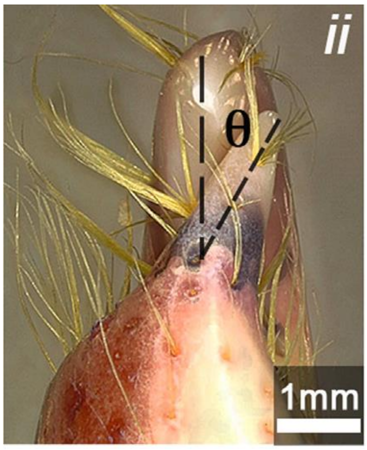

Fig. 4. The offset on the snapping claw

In 2018, Shahrouz Amini in School of Materials Science and Engineering at Nanyang Technological University conducted a multi-scale structural/nanomechanics relationship study of the snapping claw to analyze its mechanical response to contact stresses[5]. The structural analysis revealed that the tip region of the snapper claw was exclusively made of crystalline calcite, which was more brittle than other mineralized biotools, exhibiting accelerated wear damage under contact stresses. However, due to an angular offset between the dactyl and propus of the snapping claw, the appendage never engaged in any mechanical contact during the snapping action(Fig.4). This also proved that the noise produced by snapping shrimp only comes from the bubble collapse.

In the same year, the research team of Key Laboratory of Bionic Engineering at Jilin University characterized the surface material of the snapping claw, and a four-layer structure was observed in the cross section of the snapping claw, consisting of epictucle, exocuticle, endocuticle and membranous layer[6]. The unique and lightweight structure helped the snapping shrimp to protect the claw from mechanical injuries during rapid closure. Besides, cone-shaped micropapillae units on the dactyl play a role in the rapid closure motion of the snapping claw by change the interaction between the turbulent around the wall from sliding friction to rolling friction, which contributed to drag reduction.

2.2 Research on the Jets Produced by Snapping Shrimp

In 1974, Howard Schein in University of Illinois measured the intensity of sound produced by the snapping shrimp through experiments to be about 30dB[7]. By comparing the claw size of the males and females, it was concluded that the sound produced by the snapping shrimp was positively correlated with the claw size. While other researchers measured the sound produced by the snapping shrimp with source levels as high as 190 to 210 dB referenced to 1μPa at a distance of 1m[8,9].

In 1999, J. Herberholz & B. Schmitz in Institute of Zoology at University of Munich studied the physical characteristics of the jet flow of the snapping shrimp[10-12]. The study showed that the distance, width and speed of the jet had a strong positive correlation with the size of the snapping claw. In addition, males with equal snapper claw size as females produce significantly faster water jets.

In 2000, Detlef Lohse in University of Twente obtained the entire process of rapid closure of the snapping shrimp and the development of cavitation bubbles through high speed camera(Fig.5). The closure velocity of the claw was about 3500rad/s and the water jets velocity was estimated by the expansion rate of the cavitation bubbles to be about 25m/s[13].

In 2001, Detlef Lohse used high speed camera testing for further research[14,15]. By setting up the calibration photodetector and the water detector to detect the light source and the sound pressure, the test proved that the sound was generated when the snapping shrimp is closed is caused by the rupture of the cavitation bubble, not the closure of the shrimp and shrimp. The test also confirmed that at the moment of cavitation bubble collapse, there would be a very short duration of shrimp light(Fig.6).

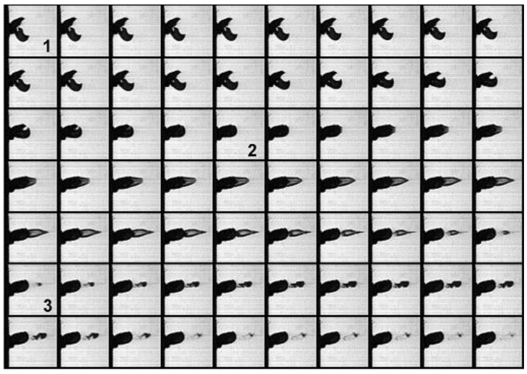

Fig. 5. the process of snapping and cavitation


Fig. 6. The shrimp light

In 2013, David Hess in Institute of Mechanics and Fluid Dynamics at Technical University of Freiberg designed a magnified transparent model based on the cross-sectional plane of the snapping claw(Fig.7). They used this model to imitated the closure of the snapping claw, and high speed camera was used to capture PIV-image to analyze the flow field of the model[16]. It was showed that vortex were formed at maximum efficiency through the claw-like model, which led to depressurization of water in front of the claw. The high speed jet did not generate high axial momentum but transfer the momentum into maximum strength of the leading vortex.

2.3 Research on the Mechanism of Cavitation in Snapping Shrimp

In 2000, Detlef Lohse used numerical simulations to explain the physical principles of cavitation bubble generation. The high speed water jet led to cavitation due to strong depressurization of water and the cavitation bubble collapsed in front of the claw. The shock wave released by the cavitation bubble collapse is about 80kPa at a distance of 4cm[11].

In 2013, An Yu in Tsinghua University further explained the principle of the cavitation bubble phenomenon of the shrimp and the cause of the shrimp light phenomenon according to the Bernoulli principle of the fluid[17]. The study also pointed out the launching shock wave and luminescence are the properties of cavitation, and the application of acoustic cavitation effect was proposed.

In 2016, Mou Jueqing in Shandong University analyzed and studied the snapping process of the snapping shrimp systematically through the principle of physical chemistry[18]. The research team calculated the kinetic energy generated by snapping and calculated the expansion work and thermal energy through the principle of bubble balance. According to the laws and methods of conservation of energy and approximation in adiabatic process, the principle of cavitation bubble formation in snapping shrimp was theoretically explained and the volume of residual gas and the temperature when the bubble collapsed were calculated. The main dissipation of energy generated by the snapping process was concluded as well as the physical and chemical phenomena in the snapping process.

In 2017, Phoevos Koukouvinis in Computer Science & Engineering at City University London used the model designed by David Hess for CFD simulation to reappear the generation of cavitation bubbles(Fig.8). The development of bubble was analyzed and it was showed the cavitation snapping shrimp generated was a kind of vortex cavitation[19]. The vortex roll-up in front of the claw when the claw was closing, leading to cavitation ring, which proved that cavitation produced by the shrimp claw was not a spherical bubble but rather a toroidal cavitation structure. The bubble volume was related to the closure velocity, and the cavitation could not happen if the closure velocity was too low.

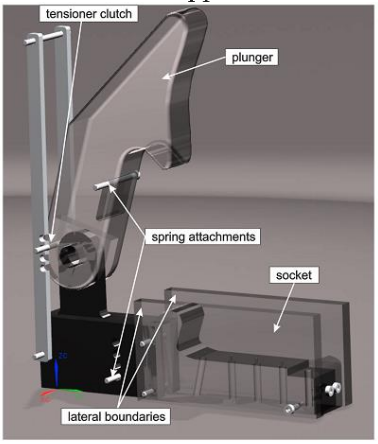

Fig. 7. The simplified model of the snapping claw

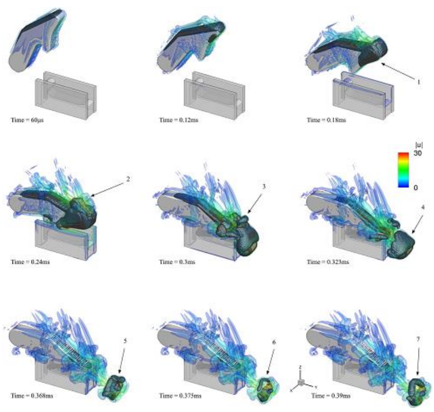

Fig. 8. Cavitation simulation of the snapping model

3. Summary and outlook

The characteristic of generating cavitation bubbles by the snapping shrimp is the result of adapting to nature after biological evolution, and the jets are focused and efficient to generate cavitation. The research on this biological characteristic can help humans to understand cavitation effect and solve problems in engineering. The current researches are focused on the creature characteristics and elucidating the mechanism of cavitation, which are at elementary stage of research. The future should be developed to bionic research, because bionic technology can guide to solve problems in engineering. The evolution of biology is mainly reflected in the biological structure, so the key to research on bionic technology is to study the effect of the claw structure on cavitation. Studying the key parameters and their effects of the snapping claw structure can provide ideas for the design of optimized cavitation generating devices in engineering.

Acknowledgments

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