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Study on the mechanics characteristics of an underwater towing system for recycling an Autonomous Underwater Vehicle (AUV)

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ABSTRACT

The towing system has a wide range of applications including aircraft launch, aerial refueling, underwater docking, and submarine topography detection. Based on aerial refueling technology, an underwater towing system for recovering an Autonomous Underwater Vehicle (AUV) is designed in this paper, which consists of one steel rod, one cable and one stable wing. First, the mechanical structure of the towing system is introduced and three steel rod models are selected. Next, the stability of the towing system is analyzed, and the numerical simulation software Star-CCM is used to study the influence of different shapes, velocities, and installation angles on the hydrodynamic characteristics of the steel rod. After the force analysis of the steel rod and the cable, the deflection of the steel rod and the vibration of the cable are studied. Through the analysis of the towing system, when the hydrodynamic center point F is located behind the center of gravity G, the towing system is more stable, the drag and lateral force of model c are smaller than that of model a and model b, and the relationship between the drag of the steel rod with the installation angle is obtained. Some other very significant conclusions are also drawn which guide the design of the towing system.

1. Introduction

In real life, there are many physical towing system applications where an object is constrained by a rod or a cable and is acted on by the fluid-dynamic forces [1]. Examples include kites, towing aircraft, towing sonar, towing glider, and aerial refueling systems. Oceans account for 71% of the area of Earth's surface, and there is a growing need to utilize AUVs for ocean exploration. To explore, monitor, and protect our oceans, we need a simple, safe, and cost-effective way of deploying and recycling our AUV assets. Due to the rapid development of the AUV and its wide range of applications, many great challenges to its recycling technology are introduced [2–4]. The traditional recycling method is to install the A-frame or other lifting device at the tail of the manned vessel to complete the recovery of an AUV on the water surface. The A-frame or the lifting device is relatively large, so the traditional recycling method has strict requirements on the condition of the manned ship. Moreover, because of the high cost, low efficiency, and high risk, the traditional manual recycling method has been unable to meet the requirements of modern underwater robots' recovery performance. With the development of Unmanned Surface Vehicle (USV) technology [5,6], people have proposed a variety of methods for unmanned recycling utilizing an AUV, which can reduce the labor intensity of operators and greatly improve work efficiency. It also allows USVs to reach hazardous areas or shallow water areas where large ships and submarines cannot go. Unlike the traditional recycling method, the main process of recycling an AUV using an USV is usually carried out underwater. Usually, an USV tows the towing system autonomously under the water, and an AUV chases the towing device at a faster velocity and completes the docking with the towing system underwater. Finally, the USV completes the recovery of the towing device and AUV. At present, the most common way for an USV to recycle an AUV is the rope-type towing method. For example, one concept design for autonomous recovery of Remus100 from a selected catamaran USV named WAM-V was designed by Florida Atlantic University [7]. An unmanned recovery system and manipulation and servicing system for different sizes of torpedoed AUV from a monohull USV was designed by the Advanced Technology & Research Corporation. A submerged docking cone towed by a USV mating with Remus 100 was designed by the Kongsberg Company [8]. However, one common feature of the towing systems mentioned is that they rely primarily on the towing method [9–11]. They all use a flexible cable to connect to the USV directly, which offers poor resistance against waves, greatly reducing the towing

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system's stability and recycling success rate.

The unmanned underwater recycling technology is very similar to aerial refueling technology. Aerial refueling is the process of transferring fuel from one aircraft to another during flight. The aerial refueling process usually consists of four stages: meeting, docking, refueling, and exiting [12–14]. The AUV's energy is not supplemented during the docking process, instead, when the AUV is placed on the mother ship it is supplemented or repaired. Therefore, the AUV recovery process is slightly different from the aerial refueling process, which includes meeting, docking, lifting, and integrated management.

For aerial refueling technology, success primarily depends on smooth docking between the probe and the drogue. The main parameters constraining the success of docking are the initial relative velocity, the pitch angle of the drogue, and the relative offset. For underwater recycling, one of the key technologies for successful recovery of an AUV is underwater docking [15–18]. However, compared to the velocity of an aircraft, the velocity of an AUV sailing in water is very slow, especially during underwater docking. Therefore, the key factor of aerial refueling is a secondary factor for underwater docking, where instead the key factors are the pitch angle and relative offset of the towing device, that is, the stability of the towing system.

By analyzing the advantages and disadvantages of the two commonly used air refueling methods, and utilizing the advantages of each refueling technology, an underwater towing system consisting of one steel rod, one cable, and one stable wing is designed to recover an AUV. The steel rod is directly connected to the USV, which can enhance resistance to wave interference. One end of the flexible cable is connected to the steel rod and the other end is connected to the stable wing, which allows the AUV and the stable wing to have relative motion. The towing system designed in this paper not only features the advantages of the current towing system, but can greatly reduce its own drag, increase the stability of the entire system, and greatly improve the recycling success rate. In this paper, the structure of the towing system is introduced and its stability is analyzed, then the hydrodynamics simulation is carried out for different shapes of steel rods in the towing system at varied velocities and installation angles. The hydrodynamic characteristics of three different steel rod shapes under different working conditions are compared. The force analysis, the deflection analysis of the steel rod, and the vibration analysis of the cable are performed, respectively.

2. Mechanical design

With the development of science and technology, the complex towing system has gradually become more simplistic. The underwater towing device was changed from what was originally an A-frame to a telescopic rod instead. The towing system is designed based on two types of aerial refueling. At present, there are two main types of aerial refueling, boom (hard refueling) and drogue (soft refueling), each with its own advantages and disadvantages [19,20].

One advantage of soft refueling is that the drogue is connected to the tanker through a hose which is very flexible and allows large displacements before attaining equilibrium configuration. When there is relative motion between aircrafts, it is also a safer option. In addition, the refueling equipment is small and tankers can therefore be equipped with three sets of refueling equipment at once, allowing it to refuel up to three aircrafts at once. The disadvantages of soft refueling include reduced speed; the flexible refueling hose is susceptible to deformation, which limits its diameter and consequently reduces speed. The refueling hose is also susceptible to airflow disturbances, which increases the difficulty of the receiver tracking the drogue to complete the docking process; it also requires greater skill from the pilot on the receiving aircraft

Hard refueling has its advantages. The boom is made of a rigid material, so it is not easily affected by airflow disturbances, and it can be designed to be relatively thick which allows faster refueling. It is suitable for rapid refueling of aircrafts that require large amounts of oil, such as transport aircrafts. Secondly, the docking process is controlled by the operator in the tanker. The receiver only needs to maintain the formation flight, which reduces the burden on the pilot on the receiving craft and also reduces the requirements on the control system. Third, the refueling equipment has different operating modes, and an automatic control system can also be designed to control the refueling process automation, or appear as auxiliary equipment for manual operation. The disadvantages of hard refueling include inefficiency: this refueling method can only deliver fuel to one aircraft at a time, and the boom has poor flexibility. If there is a large positional disturbance between the tanker and the receiver, a large docking stress will occur, which could easily cause the boom to break.

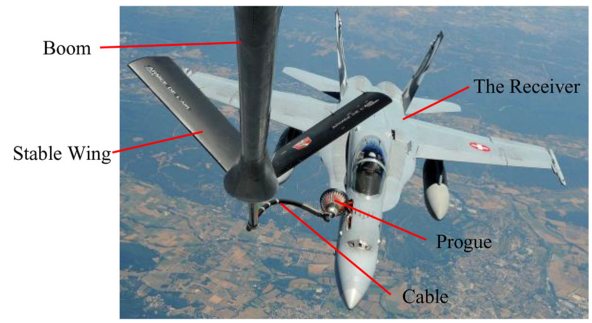

Fig. 1. The mixed aerial refueling.

If the two aerial refueling methods are combined, as shown in Fig. 1, it will make up for the shortcomings of each method. However, at present, the current mixed aerial refueling method is not often applied.

Because the process of recycling an AUV is not exactly the same as the aerial refueling process, the mothership only needs to lift the AUV and does not need to consider supplementing the AUV with energy after a successful underwater docking mission. Therefore, only one recycling steel rod is needed and the focus should be on improving the success rate of underwater docking. For a certain AUV, its maneuverability can hardly be changed, so the only way to improve the success rate of underwater docking is to increase the stability of the towing system. Combining the characteristics of two types of aerial refueling, using the advantages and avoiding the disadvantages of each type of aerial refueling, a towing system with both hard and soft components is designed. The towing system is mainly composed of a steel rod, a cable, and a stable wing, as shown in Fig. 2. One end of the steel rod is connected to the USV, and the other end is connected to the cable. The other end of the cable is connected to the stable wing. Among them, the steel rod made of rigid materials is similar to the boom, so it is not easily affected by sea current disturbances. The cable made of flexible materials is similar to the hose and has a certain degree of flexibility. When there is relative movement between the AUV and the towing system, it is safer. The role of the stable wing is mainly to improve the

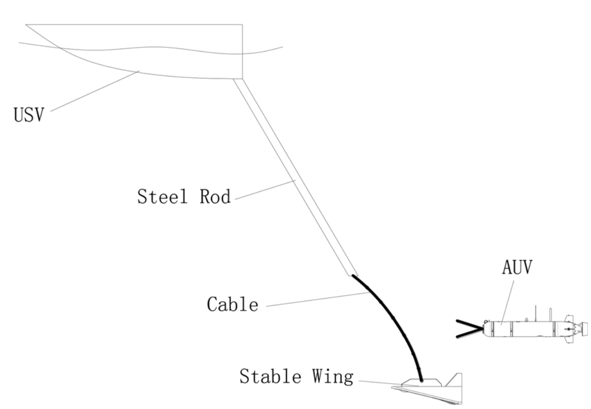

Fig. 2. The underwater towing system.