Comparison of Two Electromagnetic Couplers in an Inductive Power Transfer System for Autonomous Underwater Vehicle Docking Application

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***Abstract*—Inductive power transfer (IPT) technology provides a good solution to enlarge the working range of an Autonomous Underwater Vehicle(AUV), which plays an important role in ocean observatory. Electromagnetic coupler is the most crucial component of IPT system. In this paper, two novel electromagnetic couplers, PM coupler and reshaped EE coupler for AUV docking application were proposed. Firstly, the detail structure and fixed configuration was proposed. Secondly, the reluctance model and mutual-coupling circuit model were built. Finally, an underwater IPT prototype system was set up to verify and compare the power transfer characteristics of two different novel magnetic coupling actuators.**

Keywords—Inductive power transfer (IPT); Autonomous Underwater Vehicle (AUV); novel electromagnetic couplers; power transfer characteristics

I. INTRODUCTION

Autonomous underwater vehicle (AUV) plays an important role in ocean observatory. Currently, secondary batteries are widely used to provide power for most AUVs. Owing to the restriction of volume and weight, the working range of an AUV is severely limited by the battery capacity. In the past, the vehicle must sail to the mothership or shore base to charge, therefore part of the energy was wasted on the round trip rather than the working route. Seafloor observatory networks[1] and AUV docking technology[2] have been developed successfully in recent years, which make it possible to transfer power via the seabed cable and recharge AUVs from submerged docks or energy node in deep sea environments, thus extending an AUV's duration and enlarging its working range. A reliable connector is of significant importance to conduct the power from the seafloor station to AUV, also is a major challenge to AUV charging technology because of the conductive property of water, complex sealing structure in high pressure underwater environment and unstable docking position between the AUV and underwater station. Despite the mature technology in wet connector, the docking operation between wet connectors of AUV and undersea base is difficult. Additionally, traditional wet connectors suffer wear and are prone to arcing, making frequent maintenance a necessity, resulting in decrease in reliability and increase in cost[3-5].

Inductive power transfer (IPT) technology has been investigated for decades and widely utilized in various applications such as power supply for electrical vehicles and robots[6-7] portable electronic devices[8], airborne radar[9] and implantable bio-medical electronics[10].In general, the IPT system consists of three parts: a pack of loosely magnetic coupled actuators (usually comprises 2 or more actuators), a transmitter that provides AC power of high frequency for the primary side of loosely magnetic coupled actuator, and a receiver converts the high frequency AC power into DC power or industrial frequency AC power to supply power for the load. Since the transmitter and receiver are independent with no mechanical connection, the IPT system realizes non-physical connection between power and load. It overcomes several disadvantages of wet-mate connector mentioned previously, making it has also been applied to underwater environments to charge AUVs. Feezor et al. [11-12] designed an inductive system, which provides 200 W of power and a 10 BaseT ethernet communications interface between the dock and the MIT/WHOI Odyssey II AUV within an Autonomous Ocean Sampling Network (AOSN). Kojiya et al. [4-5] developed an automatic non-contacting power feeding system to AUV, the system could achieve the efficiency above 90% with the maximum power of 500 W or 1000 W.(20150520) McGinnis et al.[13] developed an inductive power transfer system for an underwater mooring profiler operating on a cabled deep-ocean mooring sensor network. Power transfer across the inductive couplers was approximately 240 W with 70% efficiency at a physical gap of 0-5mm. Yoshioka et al.[14] proposed a noncontact power feeding and data-transmission system for an underwater sensor installed at an ocean observation mooring buoy. Power of about 180 mW could be supplied to the sensors and bidirectional signal transmission between sensors and the water-surface located buoy could be accomplished. Li and Zhou et al. [15-16]designed a contactless inductive power transmission system, which was able to transmit power to actual undersea observation network equipment underwater with an efficiency of approximately 85% and a 5 mm gap distance.

In an inductive power transfer system, the loosely magnetic coupled actuators are the most crucial part. It decides the transmission capacity and performance of whole IPT system. AUVs and underwater bases working environment suffers from unstable gap, misalignment and eccentricity caused by stream concussions, fluctuation or docking errors, thus brings great challenges to actuator design. The coupling mode, gap distance and relative movement between couplers must be taken into consideration in actuator design for a certain

IPT system. Some special actuator structure were proposed for underwater applications. Assaf et al.[17] promoted an innovative actuator that transfer electric energy from a burrow-like docking station to autonomous underwater biorobots. In this actuator, the secondary magnetic core section was designed to be placed inside a bioinspired robot. The primary part, which was placed in a docking unit outside the robot, was divided into six sections mounted around the secondary to maximize the coupling area. For AUVs' power supply applications, Kojiya et al.[4-5] developed a cone-type coil and actuator with special structure that allowed stable underwater vehicle battery charging. Han et al.[18] proposed a cylindrical actuator in IPT system for seafloor geodetic observing robot. Granger et al.[19-20] designed a circular arc actuator and tested it in a UUV Proteus docking/recharging pod that opened for launch and recovery. Cheng et al.[21] investigated the differences between the core structures of semi-closed and non-closed actuators and found that a novel underwater loosely coupled actuator based on the semi-closed magnetic core structure could achieve better transfer performance. Wang et al.[22] presented a pack of magnetic core actuators, its secondary part was installed in the front-head section of AUV and the primary one was located in the docking base.

This paper focuses on two novel magnetic coupling actuator aims at the caged-like AUV docking[23-24], which is the maturest docking method among several different docking techniques. Firstly, the detail structure and fixed configuration were proposed. Secondly, the reluctance model and mutual-coupling circuit model were built.. Finally, an underwater IPT prototype system was set up to verify and compare the power transfer characteristics of two different novel magnetic coupling actuators.

II. THE STRUCTURE DESIGN AND FIXED CONFIGURATION OF LOOSELY COUPLED ACTUATORS

A. PM Coupler

This actuator was built to installed on the front-head cabin of AUV. Its structure fixed configuration was illustrated as Fig 1.

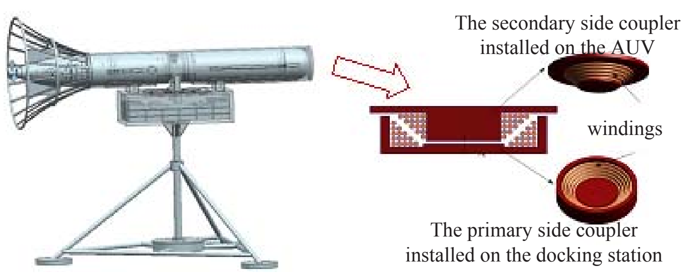

Fig.1. PM coupler installed on the front-head cabin of AUV

The actuator consists of two parts, the primary side coupler was installed on the docking station, and the secondary side coupler was installed on the front-head cabin of AUV. That indicates the thickness of the AUV shell is the gap between the IPT system's electromagnetic couplers. As Fig.1 shows, the cone-type coil was selected to get a better transmission characteristics. Moreover, it brings good fixation effect between the docking station and AUV with electromagnetic force during power feeding process.

B. Reshaped EE coupler

The reshaped EE coupler, which was mounted to the power cabin of AUV, Fig.2 illustrates its structure.

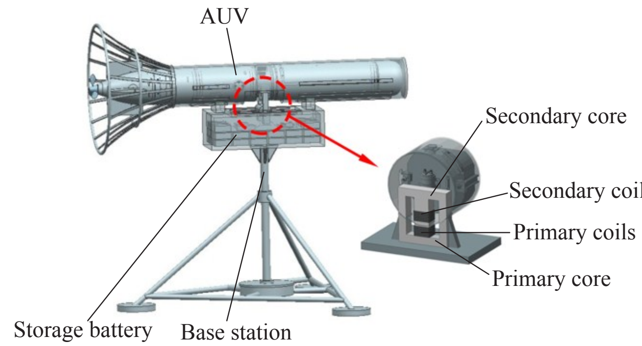

Fig.2. The structure and fixed configuration of loosely coupled actuator

The reshaped EE magnetic coupling actuator is modified from traditional EE shape. The pole of "E" is manufactured according to the diameter of usual cylindrical AUV. In this work, LP4 Mn-Zn soft power ferrite material is selected to make the actuator, their relative permeability being about 2300. This paper aims at the 200mm-diameter AUV. This set of actuator also comprised of the primary and the secondary part.

For cylindrical AUV power supply application, the primary part of actuator is mounted on the docking station and the secondary part is fixed on the AUV's power cabin respectively. Fig.2 demonstrates the fixed configuration of actuator between the underwater base and AUV. The actuator is protected by a length of rubber-made shell, which is insulative.

Compared to the actuator installed on the front-head section of AUV[22], the reshaped EE actuator is mounted to the power cabin of AUV. The latter has larger coupled area, making it has better tolerance to misalignment between AUV and docking station, since it often exists roll-aberrancy to the axis for AUV's movement. Furthermore, the front-head section of AUV usually remained for the navigation part, which consists of some magnetic devices. If the actuator is installed in the front-head cabin, it easily cause infaust influences to navigation system while the IPT system is working.

III. RELUCTANCE MODEL AND MUTUAL-COUPLING CIRCUIT MODEL

A. Reluctance modeling

Since the flux lines and paths of PM coupler or similar structures couplers have been widely analyzed in many former work or paper[4-5, 15-16, 22], great emphasis was placed on the reshaped actuator.

Over theoretical analysis and FEA (finite element analysis) method, the distribution of flux lines in the magnetic coupling actuator was shown as Fig.3. Also the flux path in novel magnetic coupling actuator were found as Fig.4 shows, including the main flux and leakage flux paths.

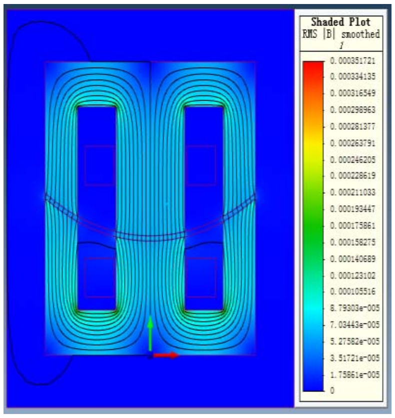

Fig.3. The distribution of flux lines in the reshaped EE magnetic coupling actuator

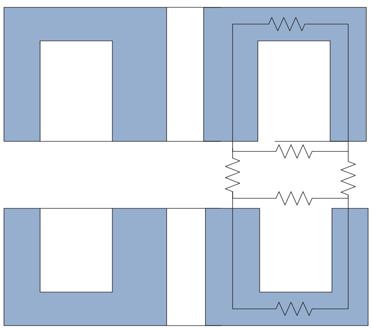

Fig.4. The flux path in the reshaped EE magnetic coupling actuator

A proper magnetic reluctance[25], whose value is related with the material permeability, the cross-sectional area and the length of the path, was introduced to derive the equivalent magnetic circuit as Fig.5 illustrates. In Fig.5, R_{m_c1} and R_{m_c2} refer to the magnetic reluctance of primary magnetic actuator and secondary magnetic coupler, respectively. R_{m_g1} and R_{m_g2} are the magnetic reluctance of inner gap and outer gap between primary and secondary couplers, and R_{m_lk1} and R_{m_lk2} are the magnetic reluctance of leakage flux paths in primary and secondary sides, respectively. The equivalent magnetic circuit can be divided into three sub-loops, α , β and γ. The flux of sub-loop α passes through both primary and secondary magnetic coupling actuators, so it corresponds to the magnetizing circuit, whereas sub-loops β and γ are the leakage magnetic circuits.

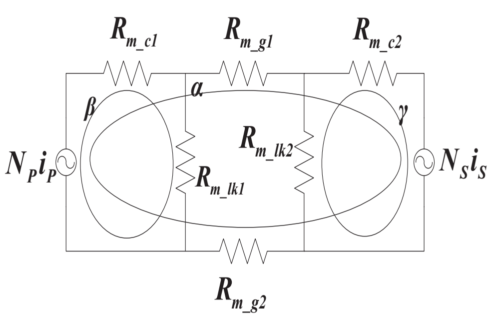

Fig.5. The equivalent magnetic circuit of reshaped EE magnetic coupling actuator

B. Mutual-coupling circuit modeling

Take the physical separation into consideration, the magnetic actuator work in loosely–coupled condition. The equivalent circuit model for the magnetic coupling actuator is shown as Fig.6. It consists of an ideal transformer and magnetizing circuit.

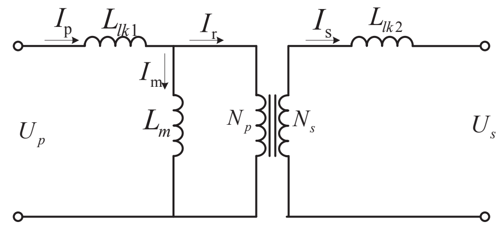

Fig.6. The equivalent circuit model of reshaped EE magnetic coupling actuator

In Fig.6, magnetizing inductance L_m and leakage inductances L_{lk1} and L_{lk2}, can be described by self-inductances L_p and L_s and mutual inductance M, which can be measured directly by an LCR meter.

In IPT system, SP compensation topology, which means a series capacitance in the primary side and a parallel capacitance in the secondary side, was used in order to overcome the low coupling and transferring power and efficiency of the system. Thus, the mutual-coupling circuit modeling was deduced from Fig.6. In this process, the resistance of conduction wire of this whole IPT system was omitted.

Fig.7 shows the mutual-coupling circuit model of reshaped EE magnetic coupling actuator. In this figure, C_p and C_s refer to compensation capacitance. R_L is the resistance of load.

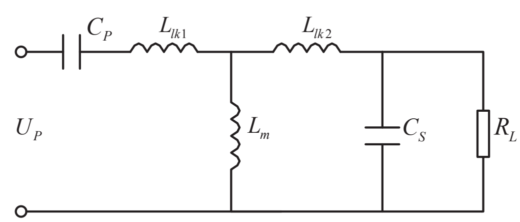

Fig.7. The mutual-coupling circuit model of reshaped EE magnetic coupling actuator

Compared with some paper [15-16, 22], the reshaped EE actuator and traditional PM coupler share the same reluctance modeling and mutual-coupling circuit modeling.

IV. Experimental Verification and Comparison

An underwater IPT prototype system was set up to verify and compare the power transfer characteristics of two different novel magnetic coupling actuators. The IPT prototype system consists of DC power source, oscilloscope, electromagnetic coupler and electronic load. Fig.8 shows the prototype system components.

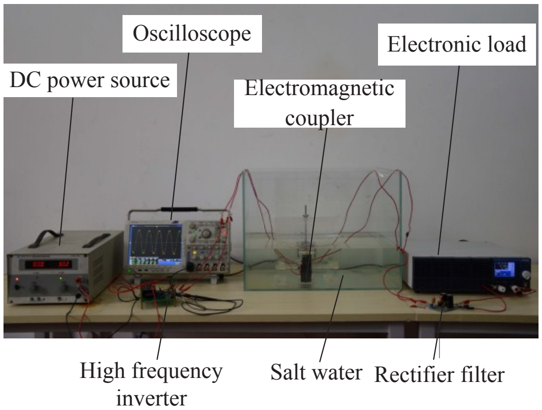

Fig.8. An underwater IPT prototype system

Test the power transfer characteristics of two different magnetic coupling actuators in 5mm gap situation, the input DC power voltage is 96V. Change the working frequency every 5k Hz from 40k Hz to 120k Hz. Fig.9 shows the test result.

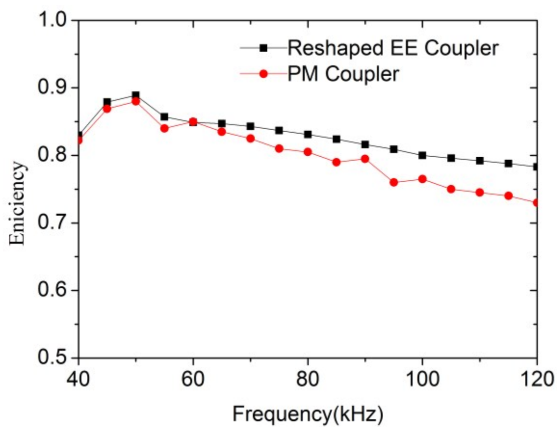

Fig.9. Test result

From Fig.9, the transferring efficiency results show the reshaped EE coupler have better transmission ability than the PM coupler. But when the working frequency of the IPT system is 60k Hz, they have the same efficiency.

V. CONCLUSION

Two novel magnetic coupling actuator aims at the caged-like AUV docking were compared in this paper. The detail structure and fixed configuration were proposed. Then, the reluctance model and mutual-coupling circuit model were built. An underwater IPT prototype system was set up to verify and compare the power transfer characteristics of two different novel magnetic coupling actuators.

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