

# Application and Performance Evaluation of Titanium Matrix Composites in Underwater Shaftless Propulsion Motors

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**Shaftless Pump-jet Thrusters (SPT) integrates the propulsion motor and impeller, eliminating the traditional propeller's transmission shaft and auxiliary components, resulting in a compact design with high efficiency. However, the stator sleeves usually generate significant eddy current losses under high-frequency alternating magnetic fields. Titanium Matrix Composites (TMCs) exhibit lower electrical conductivity and higher thermal conductivity compared to traditional titanium alloys, making them the ideal substitute for titanium alloy sleeves in motor applications. This paper systematically compares the performance of Ti-6Al-4V and TMCs through comprehensive simulation analysis of motors with different sleeve materials. The results demonstrate that employing a TMC sleeve can enhance motor efficiency by at least 5.03%. This conclusion suggests that TMCs have promising applications for sleeves in other shielded motors.**

**Index Terms**—Electrical conductivity, Sleeve, Shielded motor, TMCs, Solid loss.

## I. INTRODUCTION

With the growing demand for ocean exploration and development, Autonomous Underwater Vehicles (AUVs) are playing an increasingly important role in military, scientific research, and commercial applications. To meet the need for operation across multiple speed ranges, novel propulsion systems like Shaftless Pump-jet Thrusters (SPT) have been developed. SPT integrates the propulsion motor and impeller, eliminating the traditional propeller's transmission shaft and auxiliary components, resulting in a compact design with high efficiency and driving capability across low, medium, and high speeds[1].

Currently, most stator inner sleeves are made from titanium alloys, which provide excellent mechanical strength, corrosion resistance, and fatigue resistance. However, their relatively low electrical resistivity leads to higher eddy current losses. This not only reduces system efficiency but also increases heat accumulation, affecting equipment reliability and lifespan[2]. Therefore, introducing materials with high resistivity is crucial. TMCs not only possess higher electrical resistivity compared to titanium alloys but also exhibit superior thermal conductivity, which can significantly reduce the eddy currents losses, and facilitate efficient heat dissipation, preventing localized overheating and improving motor stability and lifespan. The material's unique properties make TMCs particularly suitable for advanced SPT applications.

This study quantitatively evaluates the benefits of titanium matrix composites (TMCs) in reducing motor losses and enhancing efficiency by comparing both computational simulations and experimental results for stator sleeves made from TMCs and Ti-6Al-4V in the same electric motor design.

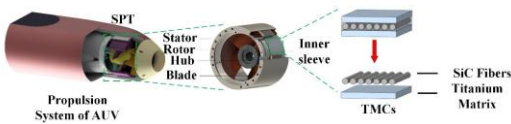


Fig. 1 Structure diagram of AUV propulsion device

## II. COMPARISON OF DIFFERENT MATERIAL SLEEVES

### A. Material measurement

Due to the anisotropy of composite materials, the electrical conductivity varies between the direction parallel to the SiC fibers and the direction perpendicular to them. Calculating eddy currents requires obtaining the equivalent conductivity of the material in the eddy current direction, which can be challenging to determine, as shown in Fig. 2.

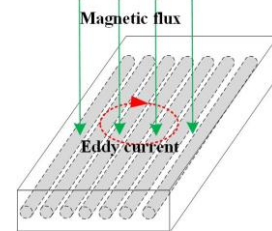


Fig. 2 Eddy current schematic diagram of TMCs

To address this issue, the first step involves measuring the material's electrical conductivity both parallel ( $\sigma_{\parallel}$ ) and perpendicular ( $\sigma_{\perp}$ ) to the SiC fiber orientation. This study presents a comparative analysis of titanium matrix composites (TMCs) and Ti-6Al-4V, with the electrical conductivity data summarized in TABLE I.

TABLE I  
ELECTRIC AND THERMAL CONDUCTIVITY OF Ti-6Al-4V AND TMCs

| Material    | Electric Conductivity(S/m) | Thermal Conductivity(W/m.K) |
|-------------|----------------------------|-----------------------------|
| Ti-6Al-4V   | 624660                     | 6.8                         |
| TMCs(Ax.)   | 285710(45.74%)             | ~20                         |
| TMCs(Circ.) | 121950(19.52%)             | ~20                         |

The results indicate that TMCs exhibit significantly lower electrical conductivity than Ti-6Al-4V in both fiber-aligned and transverse directions. Notably, in the direction perpendicular to the fibers, the electrical conductivity of TMCs drops to just 19.52% of that of Ti-6Al-4V. TMCs demonstrate superior thermal conductivity compared to Ti-6Al-4V, highlighting their potential for applications requiring enhanced heat dissipation.

### B. Electromagnetic Simulation

By inputting the electrical conductivities of TMCs in both parallel and perpendicular directions into simulations of the stator sleeve, this comparative analysis allows for a preliminary assessment of the extent to which TMCs can mitigate eddy current losses in motor applications. The main parameters of motors are shown in TABLE II. And Fig. 3 shows the 2D electromagnetic FEM model. A notable characteristic of the motor is the stringent radial dimension constraint, featuring an extremely thin radial thickness, which results in a highly compact structural design. Consequently, the permanent magnets are arranged in a Halbach array to optimize magnetic flux density distribution, thereby efficiently utilizing the available space for the stator and rotor sleeves as well as the stator core. Additionally, the motor employs a dual six-phase winding configuration, which disperses power across more phases, thereby reducing the power that each inverter bridge arm must handle.

TABLE II  
BASIC PARAMETERS OF PROTOTYPE

| Parameters            | Value           | Unit |
|-----------------------|-----------------|------|
| Rated power           | 38.7            | kW   |
| Stator outer diameter | 235             | mm   |
| Rotor inner diameter  | 188.5           | mm   |
| Axial length          | 70              | mm   |
| Slot number           | 96              | -    |
| Pole number           | 16              | -    |
| Phase number          | Double 6 phases | -    |

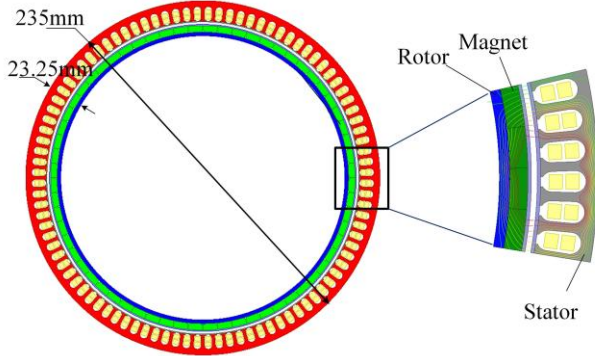


Fig. 3 2D Electromagnetic FEM model of shaftless motor

Fig. 4(a) presents the air-gap flux density distributions with different sleeve materials. The experimental results show nearly overlapping curves among the three materials, indicating that the conductivity differences in sleeves have negligible effects on the air-gap magnetic field. Fig. 4(b) presents the torque and eddy current loss under rated operating conditions. The Ti-6Al-4V sleeve shows the highest eddy current losses (4.289 kW), while SiC fiber-reinforced sleeves yield lower losses: 3.64 kW (axial) and 3.16 kW (circumferential).

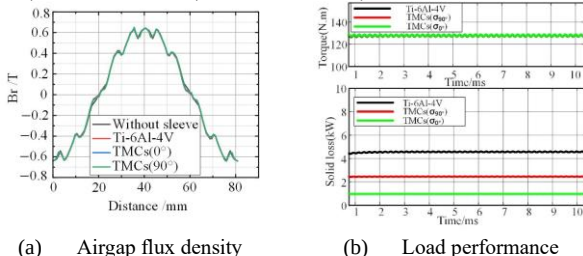


Fig. 4 Comparison of motor performance with different sleeve materials sleeves

Since torque measurement is infeasible in the shaftless propulsion motor system, the evaluation was conducted under constant-speed operation. Given identical hydrodynamic conditions, the output power can be considered constant. Motor performance comparison was achieved through input power analysis. As evidenced by the data in TABLE III, the implementation of TMC sleeves yields a minimum 5.03% enhancement in motor efficiency compared to conventional materials.

TABLE III  
COMPARATIVE PERFORMANCE OF MOTORS WITH DIFFERENT MATERIALS

|                      | Ti-6Al-4V TMCs(Ax.)TMCs(Circ.) |        |
|----------------------|--------------------------------|--------|
| Speed(rpm)           | 2900                           | 2900   |
| Torque(N.m)          | 127.68                         | 127.93 |
| Current amplitude(A) | 68.01                          | 63.01  |
| Solid loss(kW)       | 4.29                           | 3.64   |
| Input power(kW)      | 48.66                          | 45.86  |
| Efficiency (%)       | 79.68                          | 84.71  |

### III. PROTOTYPE TEST

To validate the simulation results, an experimental platform was established to test the motor performance as shown in Fig. 5. The motor performance was tested across a speed range from 500 to 2700 rpm. Fig. 6 presents a comparison between the experimentally measured power curve and the simulation results. The empirical data demonstrate a high level of agreement with the simulation results.

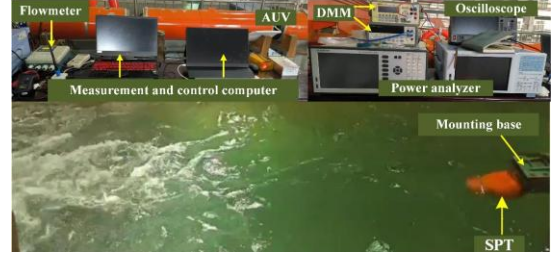
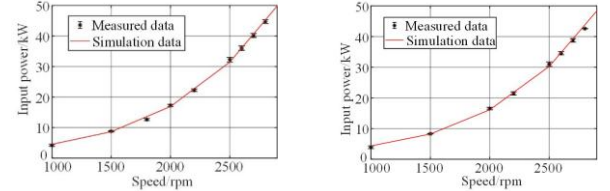


Fig. 5 Experimental Setup Layout



(a) Ti-6Al-4V sleeve (b) TMCs(Circ.) sleeve  
Fig. 6 Comparison of simulated power and experimental power

### IV. CONCLUSION

This study demonstrates that TMCs enhance motor efficiency by 5.03% to 7.64% compared to Ti-6Al-4V, attributed to their anisotropic properties. TMCs are also applicable to other types of shielded motors, offering significant improvements and broad applicability in motor design.

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