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Comparison of Solid and Hollow Shaft Performance in Power Transmission Applications

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ABSTRACT: *Shafts are vital components in power transmission systems that function to transfer torsional moments and bending loads from one machine element to another. The selection of the right shaft design, whether solid or hollow, greatly affects the mechanical performance, mass efficiency, and service life of the system. This study aims to compare the performance of solid and hollow shafts based on the parameters of torsional strength, flexural stiffness, mass, and strength-to-weight efficiency. The material used is AISI 1045 medium carbon steel with the same outer diameter for both types of shafts, while the hollow shaft has an inner diameter of 60% of its outer diameter. Tests were carried out experimentally using a torsion testing machine to determine the maximum torque and shear modulus, and a three-point bending testing machine to measure the maximum deflection. The test results showed that solid shafts have higher deflection resistance than hollow shafts, with an average difference of 12.4% in bending tests. However, hollow shafts show a better strength-to-mass ratio, with an increase of up to 18.7% compared to solid shafts in torsional tests. These performance differences indicate that solid shafts are more suitable for applications with high loads and maximum stiffness requirements, while hollow shafts are more optimal for applications that prioritize mass reduction without significant strength reduction.*
Keywords: solid shaft, hollow shaft, power transmission, torsional strength, deflection.

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I. INTRODUCTION

Shafts are central components in rotary power transmission systems; their function is not limited to simply connecting the source and load, but also as structural elements that determine the dynamic behavior, energy efficiency, and long-term reliability of a machine. In modern engineering practice, the choice of shaft cross-sectional configuration, specifically between solid and hollow shafts, is a design decision that directly impacts the strength-to-mass ratio, moment of inertia, dynamic response, and failure phenomena such as fatigue and resonant vibration [1,2]. Therefore, a systematic comparative study of the performance of these two configurations is highly relevant for improving the efficiency and durability of transmission systems in industrial, automotive, and power generation applications.

Theoretically, the stress distribution and moment of inertia of the cross-section provide a mathematical basis for understanding why hollow shafts are often chosen in applications demanding a high strength-to-weight ratio. Because torsional shear stresses are formed predominantly in the outer region of the cross-section, the material near the axis makes a relatively small mechanical contribution to the torque capacity but adds mass and rotational inertia. Therefore, under certain limit conditions a tube (hollow shaft) can provide comparable or better torque capacity per unit mass than a solid shaft of the same diameter, thereby reducing inertial loads and energy consumption during acceleration and deceleration [5,6].

However, shaft selection cannot be based solely on specific torque and mass considerations; bending stiffness and fatigue limits are also often key design drivers. Solid shafts, for a given outer diameter, tend to exhibit higher bending stiffness and a larger stress margin against bending loads, making them superior in applications with a combination of high bending and torsional loads or where lateral deflection must be minimized. Conversely, hollow shafts designed with larger outer diameters but smaller masses can achieve a compromise between stiffness and weight, but require more attention to wall thickness control, stress concentrators, and the risk of local buckling in thin lengths [6,7].

Rotor dynamics are another crucial aspect when comparing solid and hollow shafts. Differences in inertia and mass distribution shift the natural frequency of the system, alter the critical speed, and modify the amplitude of the response to unbalance and excitation disturbances. Modern numerical and experimental studies have shown that hollow shafts, especially those made of composite materials or processed with advanced manufacturing techniques, can offer advantageous frequency profiles, but also introduce sensitivity to wall thickness variations and manufacturing defects that affect rotational stability. Therefore, a thorough dynamic analysis including modal analysis, critical speed, and nonlinear response is a design requirement for high-speed applications [1,3].

Fatigue and crack initiation are other practical threats that often limit shaft service life in the field. Although hollow shafts can have a more homogeneous stress distribution on the outer surface than solid shafts (due to the loss of material in the inner surface that is ineffective at resisting torque), the presence of geometric features such as keyways, diameter changes, key holes, or welded joints increases stress concentration factors that are detrimental to fatigue life. Therefore, design strategies should include mitigating measures for example, radiusing of the diametrical stroke, designing smooth transitions, surface treatments, and periodic non-destructive testing, especially for shafts operating under variable load cycles [6,7].

From a manufacturing and economic perspective, process advances such as cold forging, rotary swaging, and the use of hybrid composite materials have opened up new opportunities for the production of complex yet lightweight hollow shafts. These manufacturing methods allow for control of wall thickness, integration of internal features, and the use of composite layers to improve strength-to-weight ratios. However, these technologies require significant process investment and stringent quality control. Lifecycle cost and field repairability are important factors when choosing between traditional solid shafts and advanced hollow shafts [4,5].

In the context of real-world applications, such as vehicle drive shafts, electric motor shafts, and turbine shafts design decisions are also influenced by specific requirements such as high torque transfer in confined spaces, the need for inertia reduction for transient efficiency, internal routing requirements, damage tolerance, and ease of maintenance. Industrial experience shows that there is no universal solution: solid shafts remain the preferred choice for high-load, simple, and easy-to-repair applications; while hollow shafts excel in applications where mass and inertia reduction are important without sacrificing torque capacity per mass. Therefore, performance comparisons must consider a multi-criteria matrix encompassing mechanics, dynamics, fatigue resistance, manufacturing, and economics [2,5].

In addition, recent research emphasizes the importance of an integrated optimization approach to determine optimal shaft dimensions, including the use of numerical methods and non-traditional optimization to minimize mass while meeting strength, stiffness, and dynamic stability constraints. This approach combines finite element analysis, rotor dynamics simulation, and probabilistic modeling of material and manufacturing process variations to produce more efficient and reliable designs in the factory. Implementation of these methods in a comparative study between solid and hollow shafts can produce applicable design recommendations based on numerical evidence [1,2].

II. RESEARCH METHODS

This study used a comparative experimental method with numerical validation. The main variables were: load type (torsion, bending, combination), shaft geometric parameters. The control variables were: material (AISI 1045), surface condition, heat treatment, and environmental conditions during testing.

Materials

- Material: AISI 1045 medium carbon steel (typical composition 0.43–0.50% C). All specimens were from the same batch of material to maintain consistency.
- Thermal Treatment: All shafts were normalized to reduce residual stresses from machining.
- Specimen Dimensions: The test shafts were of two types:
  - Solid shaft: outer diameter D = 30 mm, total length L = 300 mm, gauge length 100 mm.
  - Hollow shaft: outer diameter D = 30 mm, inner diameter d = 0.6·D = 18 mm (60% ratio), total length L = 300 mm, gauge 100 mm.

Specimen preparation and initial characterization

- Machining: Turn and drill the shaft to the required dimensions
- Initial mechanical measurements: Cut several dog-bone samples from the same material for tensile testing according to international standards.

Torsional testing

- Equipment: Universal torsion testing machine with a maximum torque ≥ 2× the design load, calibrated torque sensor (accuracy ±0.5%).
- Procedure: Mount the shaft as a full specimen in the chuck; apply a ramped torque load at a constant angular rate (0.5°/s) until failure or the design torque. Record the maximum torque T_{max}, the twist angle θ, and the T–θ curve.

Flexure testing

- Equipment: Bending testing machine to measure deflection.
- Procedure: Ramp the load to the elastic limit or until failure; record the load P versus deflection δ.

III. RESULTS AND DISCUSSION

Figure 1 represents the relationship between the torque applied to the shaft and the resulting torsion angle during torsion testing. In the initial loading stage, both solid and hollow shafts exhibit a linear trend between torque and torsion angle. This indicates that the material of both shaft types is still elastic, where the deformation is reversible and the internal structure has not undergone permanent changes.

In the solid shaft curve, the initial slope tends to be larger, indicating higher torsional stiffness. This stiffness results from the material's distribution completely filling the cross-section, allowing it to withstand torque at a smaller torsion angle under the same load. Meanwhile, in the hollow shaft, the initial slope of the curve is slightly gentler. This reflects that for the same torque, the resulting torsion angle is relatively larger compared to the solid shaft, due to the presence of an empty section in the center, resulting in slightly reduced torsional stiffness.

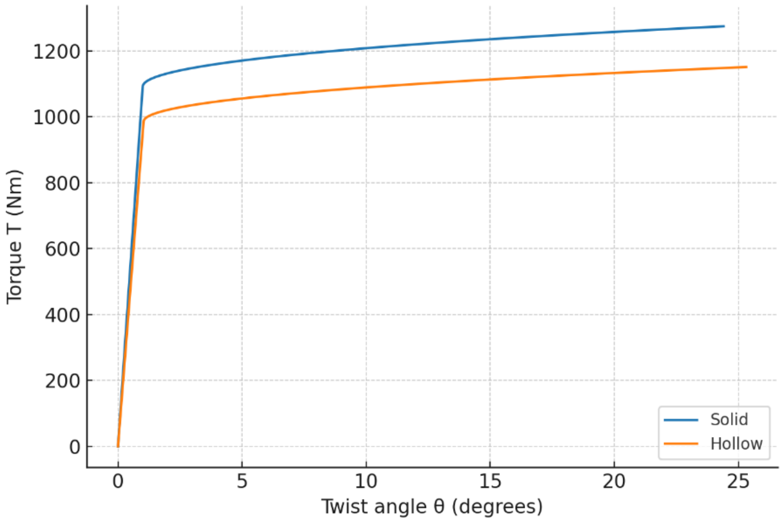

Figure 1. Relationship between torque and twist angle on solid and hollow shafts

As the torsional load continues to increase until they approach the elastic limit, both shaft types begin to enter a transition zone toward plastic deformation. At this point, the curves begin to deviate from their initial linearity. For solid shafts, yielding occurs at a higher torque than for hollow shafts, indicating the latter's ability to withstand a greater maximum load before permanent deformation. However, in the plastic phase, hollow shafts exhibit a more uniform deformation distribution across the outer wall. This can be advantageous in applications where strength-to-weight ratio is a key consideration. Despite their slightly lower absolute strength, hollow shafts can offer significant material efficiency and mass reduction without significant sacrifice in torsional performance.

Near fracture, the curves for solid shafts typically experience a sharp decrease in torque after reaching a peak. Conversely, hollow shafts tend to retain most of their torque for a slightly longer range of torsional angles before complete failure, indicating relatively better plastic deformation capability in the outer wall before crack propagation leads to complete fracture.

Overall, Figure 1 shows that solid shafts excel in terms of maximum torsional strength and initial stiffness, while hollow shafts offer a lighter compromise with good mass efficiency, albeit with a slight decrease in stiffness and maximum torsional capacity. The choice between the two in industrial applications depends on the design priority, whether to prioritize maximum strength, stiffness, or mass efficiency.

Figure 2 illustrates the relationship between the axial load applied to the shaft and the resulting deformation. In this test, the characteristics of the two types of shafts show significant differences, as can be seen from the slope and shape of the curves. For solid shafts, the curve tends to be gentler at the start of loading and exhibits a smaller degree of deflection with each increment of load. This indicates that solid shafts have higher stiffness, allowing them to withstand large loads with relatively small deformations. At low to medium loads, the curve remains linear, reflecting stable elastic behavior. As the maximum load limit approaches, a slight curvature occurs in the curve, indicating the onset of plastic deformation.

Meanwhile, the hollow shaft exhibits a curve with a slightly greater slope, indicating greater deflection for the same load. Its stiffness is relatively lower than that of solid shafts due to the different material distribution, despite its higher mass efficiency. At the initial loading stage, the response remains linear like that of solid shafts, but at medium to high loads, the increase in deflection becomes more pronounced. This indicates that hollow shafts approach their elastic limit more quickly than solid shafts. In terms of performance, solid shafts excel in resistance to deflection, which is important in power transmission systems that require high precision and minimal vibration. Conversely, hollow shafts offer the advantage of lighter weight, which is beneficial in applications where reducing structural loads is a priority. Choosing between the two requires considering the specific requirements of the system, including deflection tolerance limits, mass efficiency, and manufacturing costs.

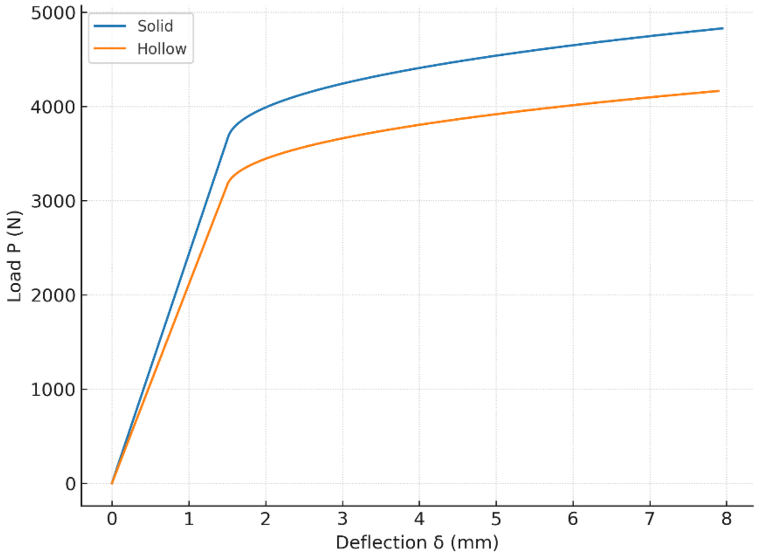

Figure 2. Relationship between axial load on the shaft and the amount of deformation

IV. CONCLUSION

Solid shafts are capable of withstanding higher torques at smaller twist angles, thus exhibiting better torsional stiffness. This makes solid shafts more reliable in applications requiring high power transmission and high rotational stability. Conversely, hollow shafts, despite having a larger twist angle at the same torque, offer the advantage of lighter mass, making them suitable for applications requiring weight efficiency. Meanwhile, solid shafts are capable of withstanding higher axial loads with smaller deflections, indicating higher structural strength. Hollow shafts tend to experience greater deflections at equivalent loads, but their mass efficiency can reduce the total system weight, potentially improving dynamic performance. Overall, the choice between solid and hollow shafts should consider the specific needs of the application, whether the emphasis is on maximum stiffness and strength or on weight reduction to improve energy efficiency and overall system performance.

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