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"Optimization of Shaft Dimensions: A Comparative Study Using Computational Method and Finite Element Analysis"

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Abstract: This study presents a novel approach to optimizing shaft dimensions, essential for efficient torque transmission in mechanical systems. Traditionally, conservative estimates lead to oversized shafts, compromising material efficiency. We developed a computational method using C programming to precisely calculate optimal dimensions for both solid and hollow shafts. The results were validated against manual calculations and finite element analysis (FEA) performed with Radioss software from Altair. Additionally, Pro-Engineer software was used for further verification. Our method demonstrated high accuracy and alignment with traditional and FEA results, providing a reliable solution for precise shaft design. This approach significantly enhances material efficiency and mechanical performance, offering a streamlined and effective tool for engineers in the field.

Keywords: *Shaft, Radioss, C language, Bending stress, Deflection, Diameter.*

Introcuction:

Shafts play a crucial role in mechanical systems across various industries, serving as essential components for transmitting power, motion, and torque between different parts of a machine. The importance of shafts stems from several key factors. [**Samuel O. et al.**]

Power Transmission: Shafts are primary components for transmitting power from a source, such as an engine or motor, to various driven components within a mechanical system. This power transmission capability is essential for enabling the operation of machinery and equipment across industries ranging from automotive to manufacturing. [**Parshuram D et. al.**].

Motion Transfer: Shafts facilitate the transfer of rotational motion from one part of a machine to another. This includes converting rotary motion into linear motion or vice versa, as well as transferring motion between different axes or directions within a system. Examples include the use of shafts in gearboxes, drive trains, and conveyor systems [**Jafar Adabi et.al**] [**M.R. Khosharavan et.al**].

Torque Transfer: In addition to power and motion, shafts are critical for transferring torque, which is the rotational force applied to a shaft. Torque transfer is essential for ensuring that mechanical systems can handle the required loads and operate efficiently without excessive wear or failure. Shafts are designed to withstand torsional stresses and transmit torque reliably. [**Jafar Adabi et.al**] [**Mannuel da F et.al.**].

Component Connection: Shafts often serve as the connecting link between various components of a machine, such as gears, pulleys, sprockets, and couplings. By providing a means of coupling and aligning these components, shafts enable the smooth and synchronized operation of the entire system [**Sumit P. Raut et.al.**].

Versatility and Adaptability Shafts come in various shapes, sizes, and materials to suit the specific requirements of different applications. They can be solid or hollow, straight or curved, and made from materials ranging from steel and aluminum to composite materials and alloys. This versatility allows shafts to be tailored to meet the performance, durability, and weight requirements of diverse mechanical systems.[**Sumit P. Raut**] [**Parshuram D et. al.**] [**Jafar Adabi et.al**].

Maintenance and Serviceability: Properly designed shafts contribute to the overall reliability and ease of maintenance of mechanical systems. They should be engineered to withstand the expected operating conditions, minimize vibration and wear, and facilitate inspection, lubrication, and replacement as needed.

In summary, shafts are integral components of mechanical systems, serving as the backbone for power transmission, motion transfer, torque transfer, and component connection. Their proper design and implementation are essential for ensuring the efficiency, reliability, and safety of machinery across industries.

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Current structural design optimization methods based on mathematical programming assume variable parameters, but in practice, design variables are often discrete due to standard sizes and construction constraints.

Tool for shaft design:

When designing shafts for mechanical systems, engineers typically refer to a combination of sources to ensure optimal performance, reliability, and safety. Here are some common sources used in shaft design.[H.G. Hall et.al]

Engineering Handbooks and Manuals Engineering handbooks, such as "Machinery's Handbook" and "Marks' Standard Handbook for Mechanical Engineers," provide comprehensive information on shaft design principles, formulas, material properties, and design considerations. These handbooks serve as valuable references for engineers at various stages of shaft design[13].

Design Codes and Standards Industry- Industry-specific design codes and standards, such as those from AGMA, ISO, and ASME, provide minimum specifications and recommendations for the design, material selection, and production of shafts. These standards ensure consistency and reliability in shaft manufacturing.

Finite Element Analysis (FEA) Software, FEA software, such as ANSYS, Abaqus, and Solid Works Simulation, allows engineers to simulate and analyze the behavior of shafts under various loads, boundary conditions, and operating conditions. FEA helps identify areas of high stress, deflection, and fatigue, enabling iterative design improvements for optimal performance and durability [**Govardhan S et. all][I.V.S. Yeswanth et.al**].

Computer-Aided Design (CAD) Software CAD software, including Pro-Engineer software Solid Works, Autodesk Inventor, and CATIA, facilitates the detailed design and modeling of shafts, including geometry, dimensions, and features. CAD tools allow engineers to visualize shaft designs, perform interference checks, and generate manufacturing drawings with precision. [**Govardhan S et. all][I.V.S. Yeswanth et.al**]

Material Databases Material databases and resources provide information on the mechanical properties, thermal properties, and material selection criteria for shaft materials. Sources such as Mat Web and ASM International's Materials Information provide access to extensive material property data for various metals, alloys, and composite materials.

Empirical Formulas and Design Guidelines Empirical formulas, such as those for calculating shaft diameter based on torque, bending stress, and torsional stress, are commonly used in preliminary shaft design. Design guidelines from textbooks, research papers, and industry best practices offer practical recommendations for shaft design parameters, such as fillet radii, keyway dimensions, and bearing fits.

Manufacturer Specifications and Recommendations For specific components, such as gears, bearings, and couplings, manufacturers often provide guidelines and recommendations for shaft design considerations, including shaft diameter, surface finish requirements, and mounting arrangements. These specifications ensure compatibility and optimal performance when integrating components into a system.

By integrating information from these diverse sources, engineers can develop shaft designs that meet functional requirements, performance objectives, and safety standards for a wide range of mechanical systems and applications.

Power transfer in circular cross-sectioned shafts often fails due to fatigue, starting at the most vulnerable spots where stress raisers, either metallurgical or mechanical, are present. In power plant systems, shafts typically experience constant torsion load with additional bending stress from self-weight or misalignment between journal bearings. [Mannuel da F].

Rotating components are vulnerable to rotating-bending fatigue, which is characterized by the initiation of cracks at stress raisers such as sudden cross-sectional changes and keyway root radii.[Berndt F et al.].Fabrication flaws or deteriorating service might nevertheless lead to fatigue failure in spite of protective design efforts. [**M.R.Khosharavan et. al.**]

For designing the Shaft, too many methods are available but all these methods are used for simple application or perform the manual calculation for getting the dimension of the solid shaft as well as hollow shaft. In this project for getting the dimension of the shaft in both cases torsional as well as bending condition are considered. First of all manual design has been performed and then after this design is compare with the analysis of the solid shaft as well as hollow shaft. After performing all these work, these designs are converted in the Programming language for getting the dimension of the shaft in few seconds.

Numerical Procedure:

Shaft is taking the total power of 30KW with the help of the gear and it is transferred to the two different application by the help of the pulleys in which one pulley transferred the 18.75 KW and another pulley is transferred the 11.25 KW. The loading condition of the shaft is shown in Fig. 1. Calculation are performed for the hollow shaft as well as solid shaft and the diameter of the shaft is found based on the stress equation and then after the deflection of the shaft is also calculated for compare the shaft al.[R.S Khurmi et.].

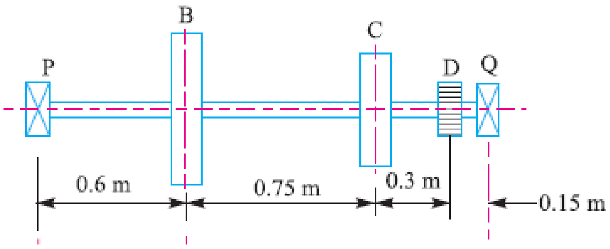

Figure 1. Loading condition of the shaft

Material of the shaft is 40C8 and the shaft is rotated with the 250 rpm. Maximum bending moment transferred generated on the shaft is calculated by the moment and reaction method by considering the shaft as a simply supported beam. Then after the torque transferred theough the shaft is found by the power equation and then after the diameter of the shaft is calculated by applying the equivalent torque equation and equivalent bending moment equation. [R.S. Khurami, J.K. Gupta]

Equivalent twisting moment generated on the shaft:

$$\mathrm{Te} : \frac{\pi}{16} * \tau * \mathrm{d}^3 : \sqrt{\mathrm{M}^2 + \mathrm{T}^2} \qquad \text{Eq. (1)}$$

Equivalent bending moment generated on the shaft:

$$M\mathrm{e} : \frac{\pi}{32} * \sigma\mathrm{b} * \mathrm{d}^3 : \frac{1}{2}[\mathrm{M} + \mathrm{Te}] \qquad \text{Eq. (2)}$$

The hollow shaft uses the same procedure, and the shaft's diameter is determined.

Deflection of the shaft is calculated for both the shaft solid as well as hollow shaft. Deflection are calculated for two loading component of the actual load applied on the shaft in horizontal as well as vertical loading component. To calculate the deflection on the shaft the Eq. (3) are used for both the cases vertical as well as horizontal loading condition and solid as well as hollow shaft.[R.S.Khurami]

$$EI\frac{d^2y}{dl^2} : -RPl + \big(W1(l - l1)\big) + \big(W2(l - (l1 + l2)\big) + (W3(l - (l1 + l2 + l3)) \qquad \text{Eq. (3)}$$

In Eq. (3), 1, 2, 3 are shows the applied load no. and respective distance of that load considered from the left hand side of the loading condition. *l* shows the full length of the shaft.

Analysis of Solid Shaft [Hyper Works Manual]

The analysis of shaft has been performed by using the Hexagonal 3D element with 10mm element size. Material of the shaft is 40C8 for the both cases solid shaft as well as hollow shaft. The results of the analysis are mentioned in following figures.

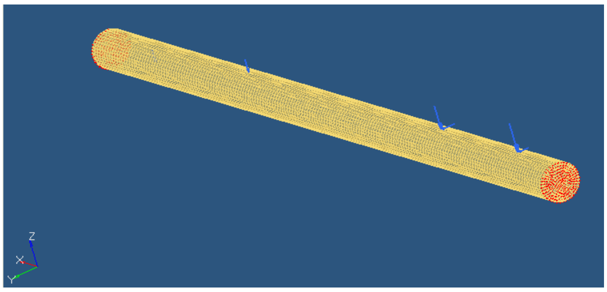

Fig. 2 : Mesh and boundary condition of the solid shaft

For performing the analysis the geometrical model is prepared on the Pro-Engineer software and then after the .IGES model of the shaft is import in the Radioss environment and then after the mesh is applied on the shaft. After applying the loading condition the analysis is performed through the Radioss software of the Altair Hyper Works. The displacement, the von-misses stress and shear stress results are shown in Fig. 3 to Fig. 5.

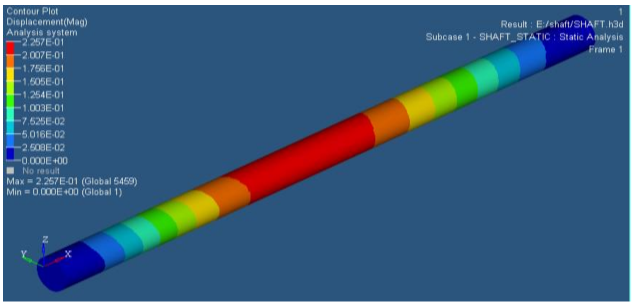

Fig.3 : Displacement magnitude of the solid shaft

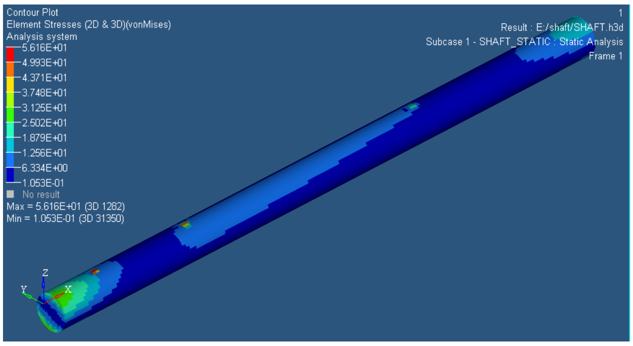

Fig. 4 : Von-Misses stress for Solid shaft

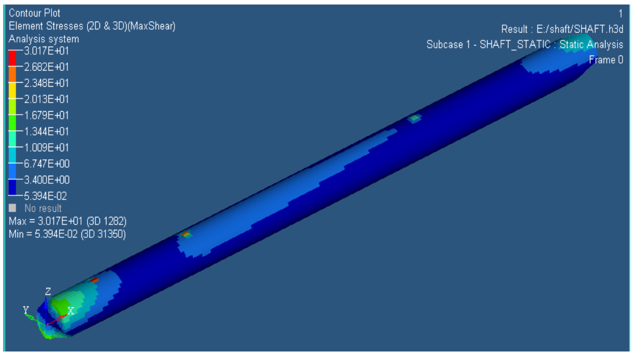

Fig. 5: Shear stress for Solid shaft

Analysis of Hollow Shaft:

After performing the Numerical calculation for the stresses and displacement the .IGES file of the hollow shaft after making in the Pro-Engineers environment import in the Radioss environment and perform the analysis same as the analysis procedure of the solid shaft. The results of the hollow shaft for Displacement, Von-misses stresses and Shear stresses are shown in the Fig. 6 to Fig. 8.

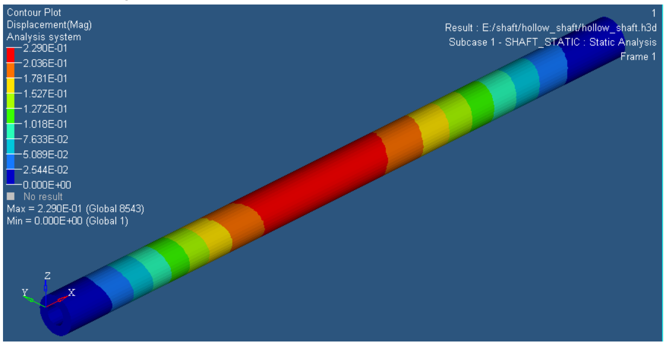

Fig. 6 : Displacement magnitude of the hollow shaft

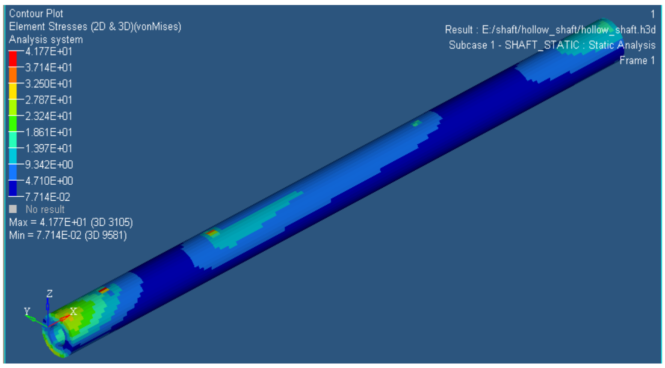

Fig. 7 : Von-misses stress for the hollow shaft

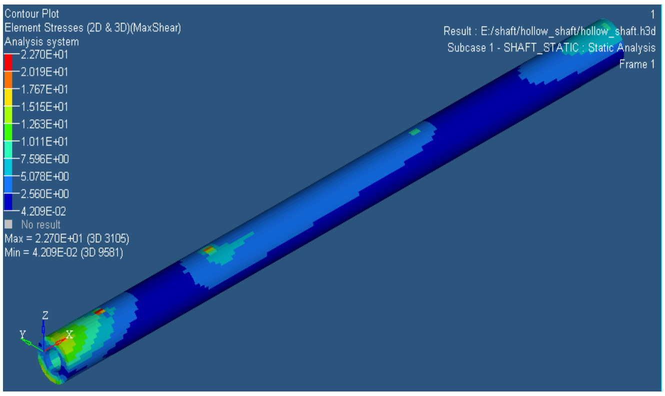

Fig. 8 : Shear stress of the solid shaft

Programming Of The Shaft:

Numerical calculation and Simulation of the component are feasible at the research work or at the new design of the new component. Each and every time it is not feasible. Due to this reason here through the programming of the shaft for simply supported beam, the time consume for the calculate the diameter of the shaft are reduce through programming of the numerical calculation of the shaft in "C" language programme. The flow chart used for making the "C" programme is shown in Fig. 9.

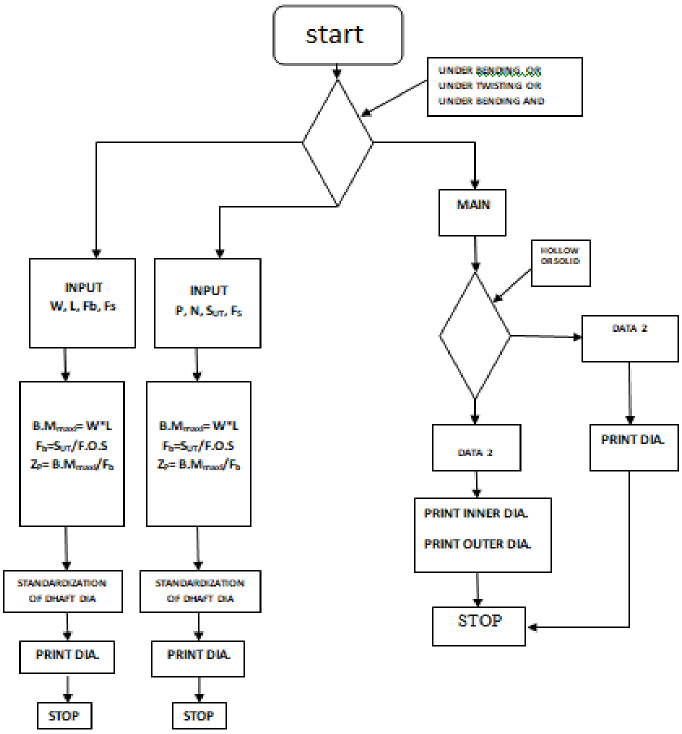

Fig. 9. Flow chart for the Solid Shaft and Hollow shaft.

During the execution of the "C" programme the input parameter are Load "W" applied on the shaft, the "L" length of the shaft and the distance of the load from the bearing support " *l* ", the design stress of the shaft in tensile as well as yield.

After execution of the shaft programme and diameter of the shaft for hollow section as well as diameter of the shaft for solid section.

Conclusions:

After performing the all types of the work such as numerical calculation, Analysis of the shaft and the programming of the shaft on the bases of the numerical calculation the results getting from both methods are compared.

The von-misses stress, shear stress and displacement of the shaft for solid section as well as hollow section are mentioned in the Table 1.

Table 1: Result Table of the Shaft

Sr.No.	Parameter	Numerical Calculation		Analysis	
		Solid Shaft	Hollow Shaft	Solid Shaft	Hollow Shaft
1	Displacement (mm)	0.244	0.222	0.226	0.229
2	Von-Misses stress(N/mm^2)	62.90	59.50	56.16	41.77
3	Shear Stress(N/mm^2)	32.14	30.40	30.17	22.7

After getting the results from all methods, value of the displacement, von-misses stress and shear stress are close to each other.

The value of the stresses for the hollow shaft in both methods has a more difference then the results of the solid shaft. According to the table the von-misses stress, shear stress and displacement has a less amount then the amount of the solid shaft in both type of work numerical as well as result from the analysis.

From the all works performed in this projects following conclusions are conclude.

Hollow shaft is better than the solid shaft for the same application.

"Programme" is easily adopted for the application due to less difference between the numerical calculation result and results getting from the analysis.

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