A New Model for Shaft Design of Engine Using MATLAB-GUI

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ABSTRACT

Shaft design is still has the most significant effect in design of machine elements as shafts are common elements in aircraft engines, gear boxes and mechanisms. In this paper, a MATLAB code is established to obtain the optimum shaft design automatically. A friendly Graphical User Interface (GUI) is developed to receive all design parameters such as; rotational speed, transmitted power, shaft material…etc. the proposed GUI also receives design parameters of shaft components such as pulleys and gears. Two case studies are introduced to illustrate the proposed shaft design tool to confirm its validity. All reaction forces, bending moment diagrams and torque diagrams are obtained using the proposed MATLAB code. These results are consistent with manual traditional design calculations.

Keywords : Shaft Deign, Optimization, MATLAB, Graphical User Interface

I. INTRODUCTION

Mechanical shaft is a component of circular cross-section that rotates with a predetermined speed and transmits power from a driving motor to other machine elements. Gears, pulleys, and sprockets are the most popular elements that can be mounted on a shaft power through mating gears, belts, and chains respectively. Shafts are commonly used in gear boxes of vehicles and aerospace devices. Shafts usually has stepped diameters for controlling the location of shaft components such as bearing, pulleys, gears, sprockets…etc. Shaft design involves a lot of parameters and design considerations related to the shaft material and layout as well as shaft component features. Many investigations are involved in shaft design optimization for various applications using different techniques. Kita et al. [1], used the boundary integral equation to reduce the maximum stress on the boundary below the yield stress of the shaft

material and to maintain the even cross-sectional area during the iterative process. Evolutionary structural optimization (ESO) was applied by Yong-Han Kim et al [2], to reduce the total shaft weight and the resonance magnification factor by removing the ineffectively used material from the design domain. Additionally, the restrictions on critical speed and bending stresses were taken into consideration. Allaka et al. [3], constructed a MATLAB code to design all solid shafts mounted with number of pulleys and gears using maximum shear stress theory and maximum normal stress theory. Moreover, Rompicharla and Rambabu [4], replaced conventional two-piece steel drive shafts with Kevlar /Epoxy as composite materials to minimize the weight of composite drive shaft. Furthermore, deflection, stresses and natural frequencies under subjected loads were evaluated using FEA. Stocki, R., et al. [5], applied a robust optimization technique to reach the optimal balance between reducing the rotor-shaft weight and assuring its admissible bending flexibility. The robust optimization technique was based on using Latin hypercube in scatter analysis of the vibration response. Sastry and Devi [6], presented a mathematical models to predict the outer diameter of a typical hollow Shaft with the help of response surface methodology as a statistical approach of design. Prasanth and Prabhu [7], used Genetic Algorithm to obtain the minimum weight and stress for an automotive manual transmission shaft with the design constraints such as natural frequency, and static strength. Finite element modeling based on shell element was used by Gubran and Gupta [8] to design automotive propeller shafts made of different materials. Shaft weights, buckling torque and dynamic performance for different design alternatives, were considered. This technique ensured the possibility of designing a single-piece propeller hybrid shaft made of fiber-reinforced composite and aluminum tube having less weight compared to that of steel shaft and having its fundamental natural frequency above the shaft operating speed. Maheta and Patel [9], presented study covers design, analysis and development of driveshaft for automobile applications using FE analysis using ANSYS software. Optimization included weight reduction of drive shaft up to about 80% by using composite material Instead

of steel material. Cherniaev and Komarov, [10], considered carbon/epoxy drive shaft design as composite drive shafts used in automotive and aeronautical applications due to lightweight combined with exceptional strength and stiffness. Lai and Zeng [11], used Multi-objective Genetic Algorithm (MOGA) which integrated in ANSYS Workbench to solve the optimization model of shafting alignment in ship operation. Liu et al. [12], performed defects analysis and tool optimization of the hot forged automotive balance shaft based on 3D and 2D finite element (FE) simulations in order to improve forging quality and productivity. Reddy and Nagaraju [13], introduced an optimum designed drive shaft using finite element model in software ANSYS. The static, free vibration and tensional buckling analysis was made which are very much required for rotating elements like drive shafts. The optimum design was made based on tensional stiffness formula and the strength to weight ratio characteristics of solid to hollow shafts. A structure optimization design model and method of the driving shaft of twin-screw pump were presented by [14] based on response surface methodology and finite element analysis. The optimization results of a case show that the equivalent alternating stress of the dangerous spindle section reduces by 26.2 %, furthermore the maximal normal deformation decreased by 25.2 % compared with the original design. Anoop and Dhanesh [15], conducted a failure analysis and optimized the design of the shaft in a 4.5KW alternator used in rail coaches. Failure and design problems of the shaft were analyzed using finite element method. Hesham A. Abdou et al. [16], introduced software based on an integrated method of stress, deflection, and critical speed analysis to detect the optimal dimensions of different stepped shafts using MATLAB. Fatigue, deflection, and vibration analysis were conducted at the most critical locations automatically. Analysis of is then performed to check safety of resulting dimensions. Mosfequr Rahman et al. [17], considered effect of material properties, geometry, and operating angle for numerical investigation of the driveshaft design using Finite Element Analysis. Swapnil et al. [18], used ANSYS to optimize design parameters of composite drive shaft by minimizing its weight by replacement of conventional two-piece steel drive shafts with single

piece. Weight optimization of propeller shaft vehicle was investigated by Sandip R and S.S. Patil [19]. A conventional steel shaft was replaced by E-glass fiber as a composite material. Kahane Roshan et al. [20], presented a methodology for design optimization of spindle shaft that was subjected to uniformly distributed load. The deflection distribution of shaft was applied to control stability of spindle using finite element analysis (FEA) software ANSYS. Vehicle propeller shaft was analyzed by Nizam S Sakeer et al. [21] using composite material instead of conventional steel shaft to decrease amount of weight and fuel consumption. By usage of composite material single piece shaft can be implemented to decrease the power losses.

From the above literature, there were a lot of considerations and parameters which can be considered while conducting shaft designs, applications, design techniques and applied software. However, the current paper discusses four main parts: basic of shaft design, model procedures, GUI, case studies to validate the model and results.

II. Basics of shaft design

In mechanical shaft applications, the shaft usually has some shaft components such as pulleys, gears, and sprockets. When power is transmitted from one component to another, the shaft is subjected to both torque and bending moment. In this case, the shaft may be designed based on two theories: Maximum shear stress theory and Maximum normal stress theory [22].

A) Maximum shear stress theory:
According to this theory, the equivalent torque (Te) is given by:

$$T_e = \frac{\pi}{16} S s d^3 \qquad (1)$$

Where: $T_e = \sqrt{M^2 + T^2}$ is known as equivalent torque, Ss = Torsion shear stress due to pure bending moment, (T).

B) Maximum normal stress theory:
According to this theory, the equivalent bending moment (Me) is given by:

$$M_e = \frac{\pi}{32} S b d^3 \qquad (2)$$

Where: $M_e = \frac{1}{2}(M + \sqrt{(M^2 + T^2)})$ is known as Equivalent bending moment, Sb = Bending stress induced due to pure bending moment, (M).
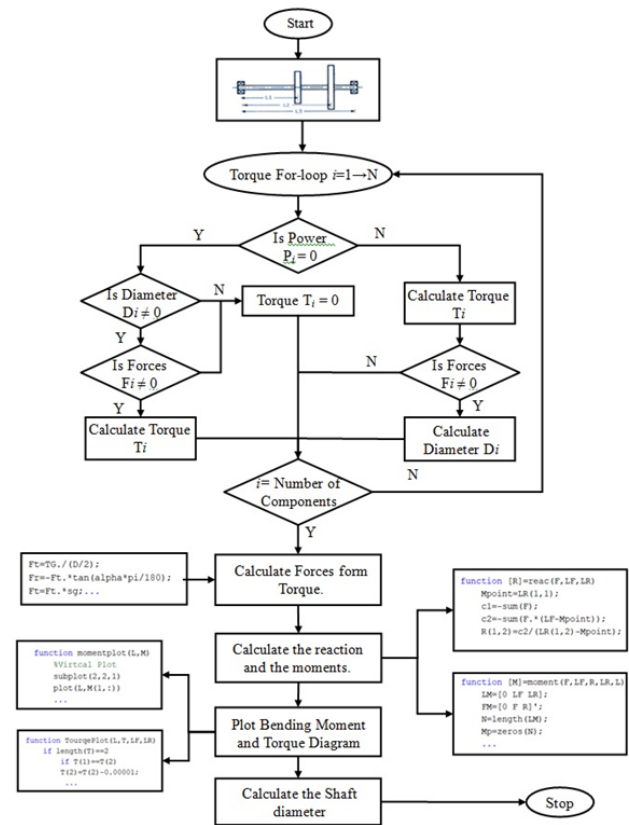

Figure (1) Code algorithm flow chart

Generally, the Guest's theory will be used for ductile material and Rankine's theory will be used for brittle material. For designing of shaft, the diameter is calculated based on both theories and the larger value will be chosen. In actual practice, the torque and bending moment may not be constant because of change of power and loads due to voltage variations, and the surroundings nature like non uniformity of roads as in case of automobiles. Hence for designing such shafts, subjected to this type of fluctuating loads, certain safety factors called shock and fatigue factors may be considered.

Where: Kb = Combined shock and fatigue factor for bending, Kt = Combined shock and fatigue factor for torsion. By including the above factors, the equivalent torque Te, may be changed as:

$$T_e = \sqrt{(K_b.M)^2 + (K_t.T)^2} \qquad (3)$$

And the equivalent bending moment Me, may be changed as:

$$M_e = \frac{1}{2}\left(K_b.M + \sqrt{(K_b.M)^2 + (K_t.T)^2}\right) \qquad (4)$$

III. MATLAB Code Procedures

All design parameters are included in the proposed MATLAB code. Theses parameters are classified into:

- Shaft parameters: such as shaft material and its properties in shear and normal stresses, shaft length, shaft speed, and direction of rotation and transmitted power.
- Pulley parameters: weight, tension forces, belt tension ratio.
- Gear parameters: weight, acting forces.
- Safety factors: Combined shock and fatigue factor for bending and torsion.
- Design equations: based on Shigley design calculations [22].

The code algorithm can be summarized in the flow chart illustrated in Figure (1)

IV. GRAPHICAL USER INTERFACE

A friendly user interface is established to organize design parameters. The GUI contains two tabs as indicated in Figure (2) to facilitate input and output data usage.

Figure (2) Proposed Shaft design GUI

A) "Inputs" Tab:

This tab is assigned to the following actions:

- Input all design data that are required to determine shaft diameter including shaft, pulley, gears, and safety factors diameters.
- Language control check box: through which user can switch between the SI unit and English unit systems.
- Execution button "Calculate" to run the code.
- Output results of shaft diameter.

B) "Diagrams" Tab:

This tab is assigned to display results of moment and torque calculations including:

- Moment diagram in vertical plane
- Moment diagram in horizontal plane
- Equivalent moment diagram.
- Torque diagram.

The working methodology of the proposed GUI can be illustrated in flow chart given in Figure (3).

V. Case Study (1)

A machine Shaft turning at 600rev/min is supported on bearing 1150 mm apart as shown in the Figure (4). The power is supplied to the shaft through a 350mm spur gear weighs 300 N and located 450 mm from the right bearing. The power is transmitted from the shaft through a 700 mm spur gear weighs 250 N and located 450 mm from the left bearing. The gear has a 20° tooth from and mates with another gear located directly above the shaft. Determine the necessary diameter using $\tau_{all} = 40$ MPa and $k_b = k_t = 1.5$.

A) Case study 1 analysis

According to the layout illustrated in Figure (4), the shaft is turning counterclockwise (CCW) at 600rpm then n = 600 rpm. The bearings are 1150 mm apart then LR = [0 1.15] in meter (written as vector). The gears are located at 450mm and 700mm from the left end then LF = [0.45 0.7] in meter. The weight of the gears are 250 and 300 N then W= [250 300]. The

pressure angle is 20 degree then alpha = 20. The gears are connected to other gears at 90 degree and the first gear from left end is the driver and the other is driven so LG = [-1 1] and ang = [90 90]. There are two loads one is 12KN resultant Force written like this [12000;0] and the other is unknown resultants force written like this [0;0].
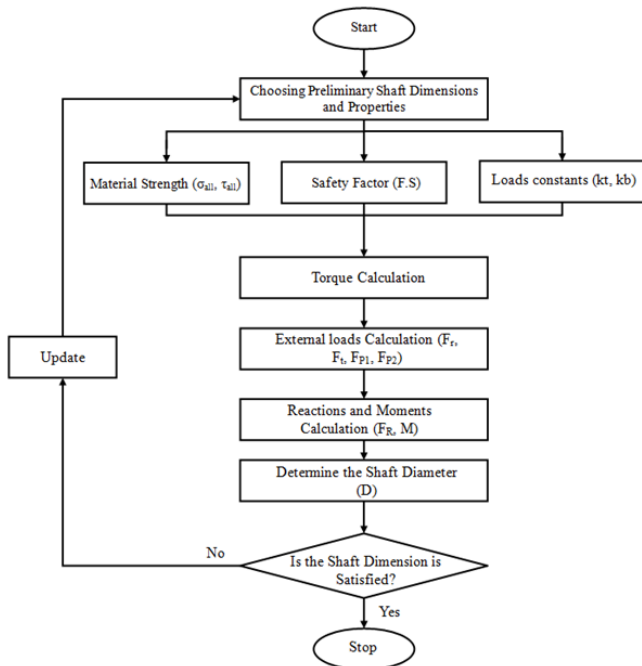

Figure (3) Design methodology of Shaft using GUI

So, FG = [12000 0;0 0]. From problem statement the allowable shear stress is 40 MPa then S = [40]. Also, k_t and k_b is equal to 1.5 then k = [1.5 1.5]. Since all the gears components are connected at the first quarter of the coordinate plane (at the positive y-axis) then p = [1 1]. Since there is no pulley and there is no power specified in the problem the following inputs will be zero P = [0 0], K= [3 1], Fp = 0 and F = 0. All these data are transformed into MATLAB code as shown in Figure (5).

B) GUI for "Inputs" tab

All parameters in "Inputs" tab are received from user as illustrated in Figure (6) and output shaft diameter is displayed when executing the code from "Calculate" button. The shaft diameter is 108 mm.

C) GUI for "Diagrams" tab

Results of moments and torque diagrams can be displayed as shown in Figure (7) in "Diagrams" tab.
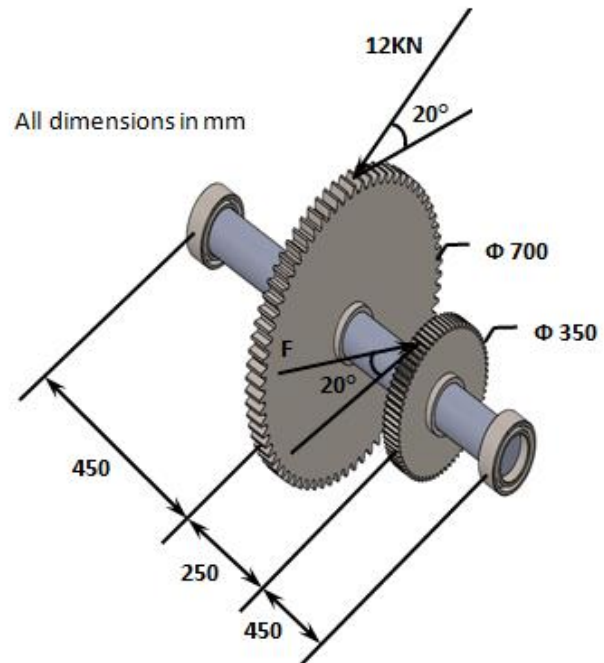

Figure (4) Layout for shaft and shaft components for case study 1

```
P=[0 0];              % Power  [W]  [-->]
n=600;                % Speed [rpm]
LG=[-1 1];            % 0 For pully 1 for driver gear -1 for driven
alpha=20;             % alpha if no Gear = 0
K=[3 1];              % Belt raito
D=[.7 .35];           % Diameter [m][-->]
ang=[90 90];          % angle in dgree [-->]
W=[250 300];          % the weight [N]
Fp=[0];               % Pully Force[N] [F1->;F2->] if any
FG=[12000 0;0 0];     % Gear Force [N] [Ft->;Fr->] if any
L=[1.15];             % Shaft Length point [m]
LF=[0.45 0.7];        % Loction of the Forcses [m]
LR=[0 1.15];          % Loction of the Reaction [m]
k=[1.5 1.5];          % [kb kt]
S=[40];               % [Shear,Normal] [Mpa]
p=[1 1];              % Locition of the Foces in Coordinate Plane
F=0;
[d]=Shff(P,n,LG,alpha,K,D,ang,W,Fp,FG,L,LR,LF,k,S,p,F);
```

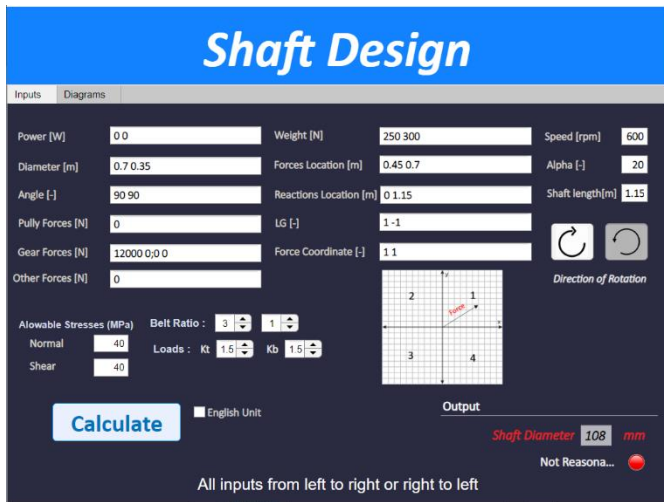Figure (5) MATLAB code inputs for case study 1

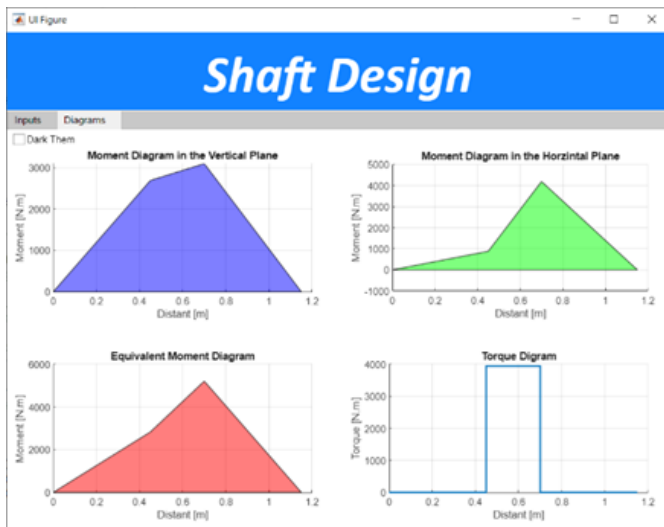Figure (6) GUI inputs for case study 1

Figure (7) Results of Moments and torque diagrams for case study 1

VI. Case Study (2)

A machine Shaft turning counterclockwise (CCW) at 600rev/min is supported on bearing 750 mm apart as shown in the Figure (8). 15 kW is supplied to the shaft through a 300 mm spur gear located 250 mm to the right of the right bearing. The power is transmitted from the shaft through a 200 mm spur gear located 250 mm to the right of the left bearing. The gear on the right weighs 800 N. All the gears have a 20° tooth from and mate with another gear located directly above the shaft. If the shaft material is selected has an ultimate strength of 500 MN/m² and

a yield point of 310 MN/m² determine the necessary diameter using K_b = 1.5 and K_t = 1.
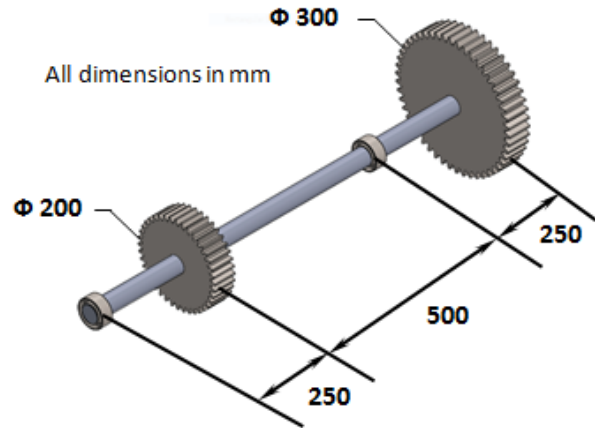

Figure (8) Layout of shaft and shaft components for case study 2

A) Case study 2 analysis

As the layout indicated in Figure (8), the shaft is turning counterclockwise (CCW) at 600rpm and the power of each component are 15kW then n = 600 rpm and P = [15000 15000]. The bearings are 750mm apart then LR = [0 1.15] in meter (written as a vector). The gears are located at 250 and 1000 mm respectively from the left end then LF = [0.25 1] in meter. The weight of the gears (from left to right) are 600 and 800 N respectively then W = [600 800]. The pressure angle is 20 degrees then alpha = 20. The gears are connected to other gears at 90 degrees. The gear in the left transmits a power to another shaft so it will be a driver gear, and the gear in the right supplies power from a shaft so it will be a driven gear LG = [-1 1] and ang = [90 90]. From problem statement the allowable normal and shear stress are 100 MPa and 60 MPa respectively then S = [60 100]. Also, k_t and k_b are equal to 1 and 1.5 respectively then k = [1 1.5]. Since the gears are connected at the first quarter of the coordinate plane (at the positive y-axis) then p = [1 1]. Since there is no pulley and the forces of the component not specified in the problem the following inputs will be zero Fp = 0, FG = 0, F = 0, and K= [3 1].

```
P=[15000 15000];      % Power  [W]   [-->]
n=600;                % Speed [rpm]
LG=[-1 1];            % 0 For pully 1 for driver gear -1 for driven
alpha=20;             % alpha if no Gear = 0
K=[3 1];              % Belt raito
D=[.2 .30];           % Diameter [m][-->]
ang=[90 90];          % angle in dgree [-->]
W=[600 800];          % the weight [N]
Fp=[0];               % Pully Force[N] [F1->;F2->] if any
FG=[0];               % Gear Force [N] [Ft->;Fr->] if any
L=[1];                % Shaft Length point [m]
LF=[0.25 1];          % Loction of the Forcses [m]
LR=[0 0.75];          % Loction of the Reaction [m]
k=[1 1.5];            % [kb kt]
S=[60,100];           % [Shear,Normal] [Mpa]
p=[1 1];              % Loction of the Foces in Coordinate Plane
[d]=Shff(P,n,LG,alpha,K,D,ang,W,Fp,FG,L,LR,LF,k,S,p,0);
```

Figure (9) MATLAB code inputs for case study 2

B) GUI for "Inputs" tab

All parameters in "Inputs" tab are received from user as illustrated in Figure (10) and output shaft diameter is displayed when executing the code from "Calculate" button. The shaft diameter is 44 mm.

C) GUI for "Diagrams" tab

Results of moments and torque diagrams can be displayed as shown in Figure (11) in "Diagrams" tab.
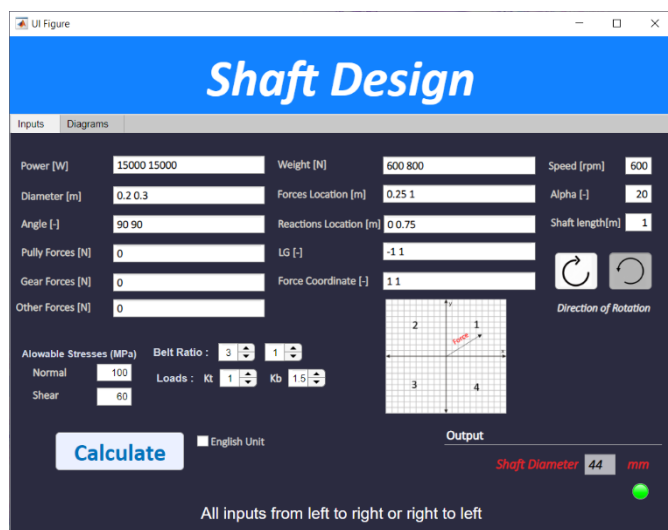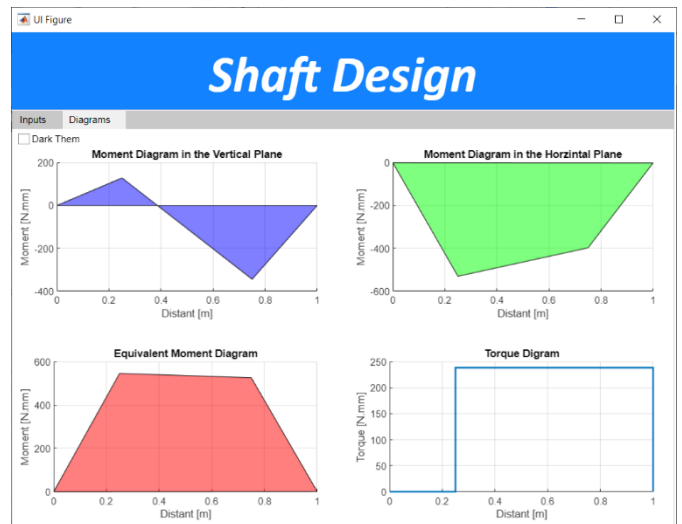

Figure (10) GUI inputs for case study 2

Figure (11) Results of Moments and torque diagrams for case study 1

VII. RESULTS

The proposed MATLAB code and GUI has been tested successfully in two case studies. All results of reaction forces, bending moments, torques and shafts diameters are consistent with manual results according to Shigley design calculations [22]. The presented GUI is simple and friendly used. Input design parameters are received by the GUI including shaft power, material, speed, and direction of rotation. Input design parameters also, includes pulley forces, belt tensions ratio, gear forces. The output shaft diameter is directly displayed when tabbing "Calculate" button. Detailed results including moment diagrams and torque diagram can be displayed from "Diagrams" tab in the GUI. In addition, user can also switch between the SI unit and English unit systems for input and output design parameters.

VIII. CONCLUSION

In this work, an efficient shaft design tool has been developed using MATLAB software based in Shigley design calculations [22]. The presented GUI can receive input data from user and display results as well. All design parameters for shaft and its associated components are included in the presented code. Two case studies are discussed to validate the efficiency of the developed code. All results agree with manual traditional design calculations. The proposed model

facilitates shaft design procedures for all applications such as vehicles and aerospace mechanisms.

IX. Acknowledgments

X. CONFLICTS OF INTEREST

The authors declared no conflicts of interest.

XI. REFERENCES

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