© 2017 IJEDR | Volume 5, Issue 2 | ISSN: 2321-9939

Design and Optimization of 2-Stage Reduction Gearbox

[1]Neeraj Patel [2]Tarun Gupta [3]Aniket Wankhede [4]Vilas Warudkar
[1 2 3]B.Tech Scholar [4]Assistant Professor
[1 2 3 4] Department of Mechanical Engineering
[1 2 3 4] MANIT Bhopal India

***Abstract*— Engineering design is an iterative process that requires to be dealt with all feasible design solutions in order to arrive at desired objective. Proper design of gearbox has a significant place in power transmission applications. Traditional methods used in its design do not have ability in automating the process. Thus an attempt to automate preliminary design of gearbox has been accomplished in the paper. Software to automate preliminary design of gearbox with spur helical and bevel gears was developed. In the software KISSsoft we apply the problem with the objective function of minimizing of volume of gear trains. The objective function was constrained by bending strength contact stress face width and number of pinion and gear teeth. The preliminary design parameters module number of teeth and width of teeth for pinion and gear pairs of the stages were optimized and gear ratios were determined in respect to the objective function and design constraints. Design optimization of a two stage gearbox by using KISSsoft was accomplished by readily supplying the design parameters requested.**

***Index Terms*—Design optimization Gearbox KISSsoft**

I. INTRODUCTION

Engineering design is an iterative process that is started with a poorly defined problem refined and then developed a model finally arrived at a solution. Due to nature of engineering design there could be more than one solution therefore a search should be conducted in order to find the best solution. As a mechanical design problem design of gearbox is very complex because of multiple and conflicting objectives.

A gearbox utilizes a group of gears to achieve a gear ratio between the driver and driven shafts. The material volume of gear trains is the main determination factor in sizing of this power transmitting units. Trail-and-error method is mainly used in traditional design of gearbox. Researchers have developed several applications using different design and calculation methods. A gearbox producing the required output speed was designed by KISSsoft. An optimal weight design problem of a gear pair system was studied using KISSSOFT. The system was able to find the number of design variables considering specified constraints. A generalized optimal design formulation to gear trains was presented. A computer aided design of gears approach was proposed to optimize one stage gear pair. KISSSOFT was employed for minimizing gear volume by reducing the distance between the centre of gear pairs and other parameters such as transmitting power reduction ratio. The KISSSOFT module was used for optimizing volumes of pitch cylinders of gears for a single reduction gearing system.

II. PROJECT REQUIREMENTS AND ENGINEERING SPECIFICATIONS

We have a desire to switch their drive train reduction from a chain to a gear reduction in order to improve efficiency. We recognized that a gear reduction will increase the weight of the vehicle but we would like the weight to be minimized so that the drive train weight does not increase the weight of the vehicle by more than 10% of the weight of the previous vehicle. We would also like to keep final gear reduction of 10.0:1. In order to meet the packaging requirements of the vehicle the drive train must work with a 0.75 inch input shaft.

- ✓ For optimal integration of the reduction box to each system and the vehicle there is a minimum distance of six inches and maximum distance of eight inches between the centerlines of each shaft.
- ✓ The width of the gear box cannot be greater than five inches.
- ✓ The friction of the drive train must be decreased by 10% when measured by using breakaway torque to rotate as the friction causes a loss of power.
- ✓ To increase the acceleration of vehicle.
- ✓ Also to increase the reliability of the power train.

III. MATERIAL SELECTION

The first step in the gearbox design process is to select the material. A material is to be selected by doing intensive research on the properties of the various materials. A material is to be selected keeping in mind the various parameters like strength weight durability cost and other parameters for the sake of designing gearbox **18CrNiMo case-carburized steel** is selected as gear material due to its better mechanical properties.

TABLE 1.GEAR MATERIAL SPECIFICATIONS

MATERIAL SPECIFICATION	VALUE
Surface Hardness	HRC 61
Tensile Strength(N/mm2)	1200
Yield Strength(N/mm2)	850
Poisson's Ratio	0.3
Young's modulus (N/mm2)	206000

45C8 carbon steel is selected as shaft material due to its better mechanical properties.

TABLE 2.SHAFT MATERIAL SPECIFICATIONS

MATERIAL SPECIFICATION	VALUE
Surface Hardness	HRC 13
Tensile Strength(N/mm2)	660
Yield Strength(N/mm2)	560
Poisson's Ratio	0.3
Young's modulus (N/mm2)	206000

IV. SPUR GEAR DESIGN

Input characteristics:

Power=7.5 KW Rpm=2048
B&G engine- 13.755 ft. lbf@2600 10 hp@3600
Input Torque=25.81 ft. lbf

Gearbox is coupled with CVTech CVT having minimum ratio of 3 and maximum ratio of 0.5.

CVT ratio=$3-\left[\frac{2.5(rpm-1800)}{1800}\right]$

Rpm = 2600 r_{cvt}=1.88 T=18.65 Nm
Rpm = 2000 r_{cvt}=2.72 T=17.89 Nm
Rpm = 2200 r_{cvt}=2.44
Rpm = 2400 r_{cvt}=2.16
Rpm = 2800 r_{cvt}=1.61
Now for wheel diameter D= 22 inch= 0.558m.

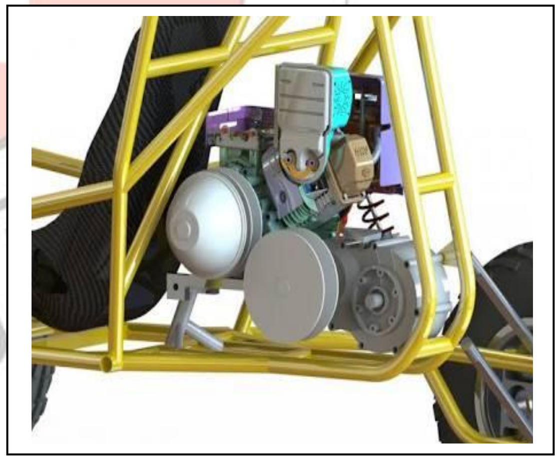

Fig.1 Powertrain Assembly

Power=Torque*angular velocity
P=T*ω=7.5*1000=35*ω ω=214.285=**2*π*N/60**
Hence **N=2047.3 rpm.**

V= $\frac{\pi*D*N}{60}=\frac{3.14*0.558*3800*0.8}{60*10*0.6}$=14.81 m/s=53.3 kmph(max.)
Hence to achieve the speed of 53kmph we required the gear reduction of gearbox as 10:1.

IV.I. 1st Stage Reduction

Following are the input parameters for first stage reduction
Ratio=3.16:1
T=35 Nm P= 7.5 KW N = 2048 rpm for pressure angle $\varphi = 20°$ min. no. of teeth=18.

IV.I.I. Module estimation on the basis of beam strength

$$\mathbf{m} = \left[\frac{60*10^6}{3.14}\left\{\frac{(kw)*C_s*f_s}{z*N*C_v*\frac{b}{m}*\frac{S_{ut}}{3}*Y}\right\}\right]^{1/3}$$

where C_s=1.5 f_s=1.5 Y=0.308 $C_v=\frac{3}{3+v}$=3/8…assuming velocity = 5m/s.
Substituting values
m=2.66 mm

IV.I.II. Module estimation on the basis of wear strength

$$m=\left[\frac{60*10^6}{3.14}\left\{\frac{(kw)*C_s*f_s}{z^2*n_p*C_v*\frac{b}{m}*Q*K}\right\}\right]^{1/3} \qquad Q=\frac{2z_g}{z_g-z_p}=\frac{2*57}{57-18}=2.92 \qquad K=0.156\left\{\frac{BHN}{100}\right\}^2$$

HRC to BHN
HB=5.97*HRC +104.7 HRC=25(for steel)
HB=254 BHN.
Hence module m=3.52 mm

On the basis of above two values the module is selected as **3mm** according to the standard value and this value of module have been verified as per design.

IV.I.III. Check for Design

$\mathbf{P_t}=\frac{2*M_t}{d_p}$=2*35000/54=1296.4 **V**=3.14*d_p*n_p/60*10^3=5.79m/s $\mathbf{C_v}$=3/3+5.79=0.34
$\mathbf{P_{eff}}$.=C_s/C_v*P_t=1.5*648.2*2/0.3412=5697.67 $\mathbf{S_b}$=mbσ_bY=3*30*400*0.308=11088N
$\mathbf{f_s}=\frac{S_b}{P_{eff}}$=1.94 design is satisfied.
So module is selected as **3mm.**

IV.I.IV. Minimum number of teeth to avoid interference

$$N_P=\frac{2k}{(1+2m)\sin^2\phi}\left(m+\sqrt{m^2+(1+2m)\sin^2\phi}\right)$$

For pressure angle= 20° $k = 1$ $m = 3$ **N_p=14.98=15(approx.)**

IV.I.V. AGMA /ANSI Procedure

Failure by bending will occur when the significant tooth stress equals or exceeds either the yield strength or the bending endurance strength. A surface failure occurs when the significant contact stress equals or exceeds the surface endurance strength. The American Gear Manufacturers Association1 (AGMA) has for many years been the responsible authority for the dissemination of knowledge pertaining to the design and analysis of gearing. The methods this organization presents are in general use in the United States when strength and wear are primary considerations. In view of this fact it is important that the AGMA approach to the subject have been used here.

Diametral pitch=1/m=25.4/3=8.46teeth/inch V=3.14*d_p*n_p/12 V=1136.1 ft/min.
W=33000*h/V=33000*10/1136.1=290.46 lbf
Face width (f)=1.18 inch.

Two fundamental stress equations are used in the AGMA methodology one for bending stress and another for pitting resistance (contact stress).

IV.I.V.I. For Bending

1. Velocity factor K_v=1200+V/1200 k_v=1.94.
2. Overload factor K_o=1.5
3. Size factor K_s=1
4. Load distribution factor K_m= 1.2
5. Rim thickness factor K_b=1
6. Geometry factor J= 0.33

σ=w_t*k_o*k_v*k_s*p_d/f*k_m*k_b/J
σ=22036.1126 psi.

$$\sigma_{all}=S_t/S_f*\frac{Y_N}{K_t*K_r}$$

1. Temp. factor K_t=1
2. Reliability factor K_r=1
3. Stress cycle factor Y_n=1

S_t=65000 psi (grade-2) for carburized and hardened steel
Bending factor of safety=65000/22036.1126 using ($\frac{\sigma_{all}}{\sigma}$)

FOS_{ben} =2.9 (design is acceptable)

IV.I.V.II. For pitting

1. Elastic coefficient C_p=2300
2. Surface condition factor C_f=1
3. Geometry factor(I)= cos$\emptyset_t$*Sin$\emptyset_t$*m_a/2*m_n*(m_a+1)
   m_a=gear ratio=3.16 m_n=1 hence I=0.12.

σ_c=C_p*($\omega_t * Ko * Kv * Ks * Km * \frac{Cf}{Dp} * F * I$)^0.5

σc=133692.96psi

$FOS_{pitting}$=$\frac{\sigma_c}{\sigma_{all}}$=2.039.

Comparing $(fos)_{bending}$&$(fos)^2_{pitting}$ i.e 1.94 & 4.16

IV.II. 2nd Stage Reduction

Torque=35*3.16=110.6 Nm Pitch line velocity(V)=3.14*2.12*648.1/12=359.52ft/min.
W_t=33000*H/V=33000*10/359.52=917.88 lbf
Facewidth=37.68/25.4=1.48 inch.

IV.II. I. For bending

1. Velocity factor=1200+V/1200 Kv=1.29
2. Overload factor Ko=1.5
3. Size factor Ks=1
4. Load distribution factor K_m=1.2
5. Rim thickness factor K_b=1
6. Geometry factor J=0.33

σ=917.88*1.5*1.29*1*8.46*1.2/1.48*0.33
σ =36918psi

FOS_{ben} =65000/36918=1.76

IV.II.II. For pitting

1. Elastic coefficient Cp=2300
2. Surface condition factor C_f=1
3. Geometry factor I=0.12

$$\sigma = 2300\left[917.88 * 1.5 * 1.29 * 1 * 1.2 * \frac{1}{2.12} * 1.48 * 0.12\right]^{0.5}=173046psi$$

$\sigma_{c\ all}$=225000*1.2*1.01/1*1=272700psi

$FOS_{pitting}$ =272700/173046=1.57

Comparing fos_b & $(fos)^2_{pitting}$ i.e 1.76 &2.46.

IV.III. Shaft calculations

As shafts are subjected to fluctuating bending and torsional stresses. Hence shafts are designed using DE-Goodman's criteria of failure as it is conservative as well as optimum as per design.

IV.III.I. For Intermediate shaft

W^t_{12}=290.46lbf W^t_{34}=917.88lbf
Wcos20= w^t_{12} W^r_{12}=105.72 lbf
W^r_{34}=334.08 lbf d_2=6.732inch
T=977.73 lbf.inch (w^t_{12}*d_3/2)

For X-Y Plane

W^r_{12}+ W^r_{34}=R_{AY}+R_{BY}=105.72+334.08=439.8
Taking moment about point A
R_{BY}*4.2393=w^r_{34}*2.9070+w^r_{12}*1.1811
R_{BY}=258.5418lbf

R_{AY}=181.258lbf.

For X-Z Plane
$w^t_{12}+R_{AZ}+R_{BZ}=W^t_{34}$
$R_{AZ}+R_{BZ}$=627.42
Taking moment about point A
R_{BZ}*4.2393+W^t_{12}*1.1811=W^t_{34}*2.9070
R_{BZ}=548.49 lbf
R_{AZ}=78.9297lbf

Calculating bending moment
For X-Y Plane
M_b=0
$M_d=R_{by}$*1.3323=344.455 lbf.inch
M_e=288.426lbf.in M_c=214.073 lbf.in
M_a=0.

For X-Z Plane
M_b=0
$M_d=R_{BZ}$*1.3323
M_d=730.753 lbf.in
M_e=456.77 lbf.in
M_c=(R_{BZ}*3.058-W^t_{34}*1.726) M_c=93.02 lbf.in
M_a=0.

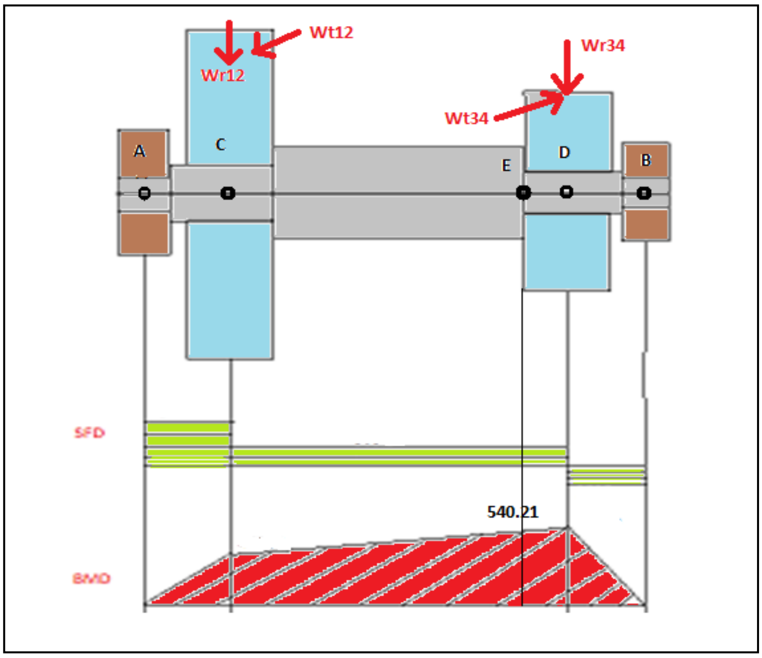

Fig.1 Intermediate shaft (SFD and BMD)

For shaft material (45 C8 Steel)
K_t=1.7 K_{ts}=1.5 Alloyed steel S_{ut}=95.0 Kpsi.
For S_e

1. Surface factor $k_a=a*(S_{ut})^b$ a=2.7 b= -0.265. K_a=0.8077.
2. Size factor K_b=0.9
3. Loading factor K_c=1
4. Temp.factor K_d=1
5. Reliability factor K_e=0.753
6. Miscellaneous factor K_f=0.5

   S_e=0.8077*0.9*1*1*0.753*0.5*95=26Kpsi

Using DE-Goodman's criteria
M_a=540.21 lbf.in T_m=977.73lbf.in
$$d=\{\frac{16*2}{3.14}*(2*K_f*M_a/S_e+[3*(K_{fs}*T_m)^2]^{0.5}/S_{ut})\}^{0.33}$$
d=0.7852 inch.
d=0.875 inch (from standard table)
End dia. range=0.726-0.728 inch.
D/d = 1.2 (std.) D= 1.2 *0.875 inch=1.125 inch.
D/d=1.125/0.875=1.2857 which is acceptable.

Assume fillet radius r=d/10=0.0875 inch
K_t=1.6 q=0.82 $k_f=1+q(K_t-1)$=1.49
K_{ts}=1.35 q_s=0.95.
$K_{fs}=1+q_s(K_{ts}-1)$=1+0.95(1.35-1)=1.33 K_a=0.8077(no change)
$K_b=(d/0.3)^{-0.107}$=0.8917.
Now S_e=0.8077*0.8917*1*1*0.753*0.5*95=25.76 Kpsi
$\sigma_a'=32*K_f*M_a/3.14*d^3$=12244.61psi
σ_m'=1.73*16*1.33*977.73/3.14*$(0.875)^{3'}$=17131.076 psi

Using Goodman equation
$1/n_f=\sigma_a'/S_e+\sigma_m'/S_{ut}$=1.54

Check for yielding
$n_y=S_y/\sigma_{max}' > S_y/\sigma_a'+\sigma_m'$=82000/12244.61+17131.076=2.8.

IV.III.II. For Input shaft
W^t_{12}=290.46lbf
W^r_{12}=105.72lbf.

T=308.756 lbf.in=309lbf.in

For X-Y Plane
$W^{r}_{12}=R_{AY}+R_{BY}=105.72$
Taking moment about point A
$R_{BY}*4.2393=W^{r}_{12}*1.1811$
R_{BY}=29.45lbf.
R_{AY}=76.27lbf.

For X-Z Plane
$R_{AZ}+R_{BZ}=w^{t}_{12}$
Taking moment about point A
R_{BZ}=80.92 lbf.
R_{AZ}=209.79 lbf.

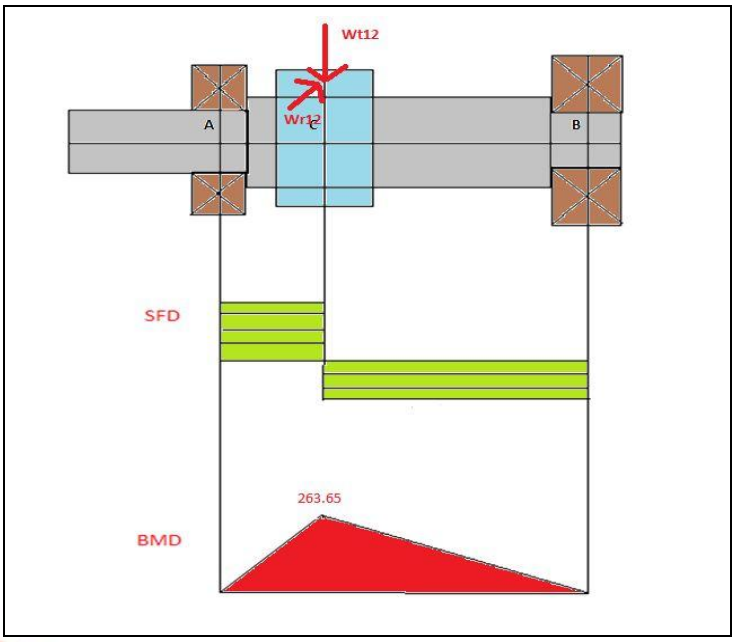

Fig.2 Input shaft (SFD and BMD)

Calculating Bending Moment
For X-Y plane
$M_b=0$
$M_c=76.27*1.1811$
M_c=90.08lbf.in
$M_B=76.27*4.2393-105.72*3.0582=0$
For X-Z plane
$M_c=R_{AZ}*1.1811=209.79*1.1811=247.78$lbf.in
$M_r=(M_{cxz}^2+M_{cxy}^2)^{0.5}$
M_r=263.65lbf.in
S_e=26Kpsi (from intermediate)

Using DE-Goodman's criteria
using $M_m=T_a=0$
M_a=263.65 lbf.in
T_m=309 lbf.in
d=0.5743 inch
d=0.6368 inch.
$K_t=1.6$ $q=0.82$ $k_f=1+q(K_t-1)$ $k_f=1.49$
$k_{ts}=1.35$ $q_s=0.95$ $K_{fs}=1.33$
$K_a=0.807$ (no change)
$K_b=(d/3)^{-0.107}$ $K_b=0.9226$
Now $S_e=0.8077*0.9226*1*1*0.753*0.5*95=26.65$ Kpsi
σ_a'=15503.337 psi
σ_m'=14045.56 psi
$1/n_f=\sigma_a'/S_e+\sigma_m'/S_{ut}=1.371$

IV.III.III. For Output Shaft
For X-Z plane
$R_{AZ}+R_{BZ}=W^{t}_{34}=917.88.$
Taking moment about point A
$R_{BZ}*4.2393=917.88*2.9070.$
R_{BZ}=629.4145 lbf
R_{AZ}=288.465lbf.

For X-Y plane
$R_{AY}+R_{BY}=W_{34}^{t}=334.08$
Taking moment about point A
$R_{BY}*4.2393=W^{r}_{34}*2.9070$
R_{BY}=229.087lbf
R_{AY}=104.9925lbf

Taking X-Y plane
$M_c=R_{AY}*2.9070=104.9925*2.9070=305.2132$ lbf.inch
Taking X-Z plane
$M_c=R_{AZ}*2.9070=288.465*2.9070=838.5677$ lbf.inch
$M_r=(M_{CXY}^2+M_{CXZ}^2)^{0.5}$=892.384lbf.inch
S_e=26Kpsi (from intermediate)

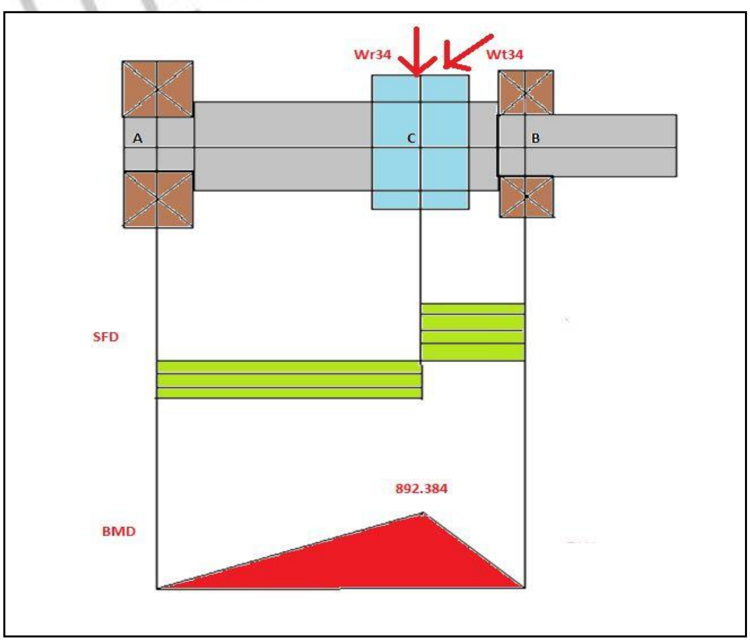

Fig.3 Output shaft (SFD and BMD)

M_m=T_a=0
M_a=892.384 lbf.inch T_m=3089.6288lbf.inch
d={32/3.14(2*0.5*892.384/26000+{[3*(1.5*3089.6288)^2]$^{0.5}$}$^{0.33}$
d=1.0658 inch
d=1.128 inch.
K_t=1.6 q=0.82 K_f=1+q(K_t-1)
K_{fs}=1.35 q_s=0.95 K_{fs}=1+q_s(k_{fs}-1)=1.33.
k_a=0.8077
K_b for$0.11 \le d \le 2$ inch
K_b=$(d/0.3)^{-0.107}$=0.8678
Now S_e=0.8077*0.8678*1*1*0.753*0.5*95=25.07 psi.
σ_a'=32*k_f*M_a/3.14*d^3=9441.28psi
σ_m'=[3*(16*k_{fs}*T_m/3.14*d^3)^2]$^{0.5}$ =25267.87 psi

Using Goodman equation
$1/n_f=\sigma_a'/S_e+\sigma_m'/S_{ut}$
n_f=1.556

V. Optimization of parameters

Optimization have been done by using the KISSsoft software.

V.I. For 1st Stage Reduction

At first power and torque are entered as the basic parameters and other parameters have been optimized in further steps.

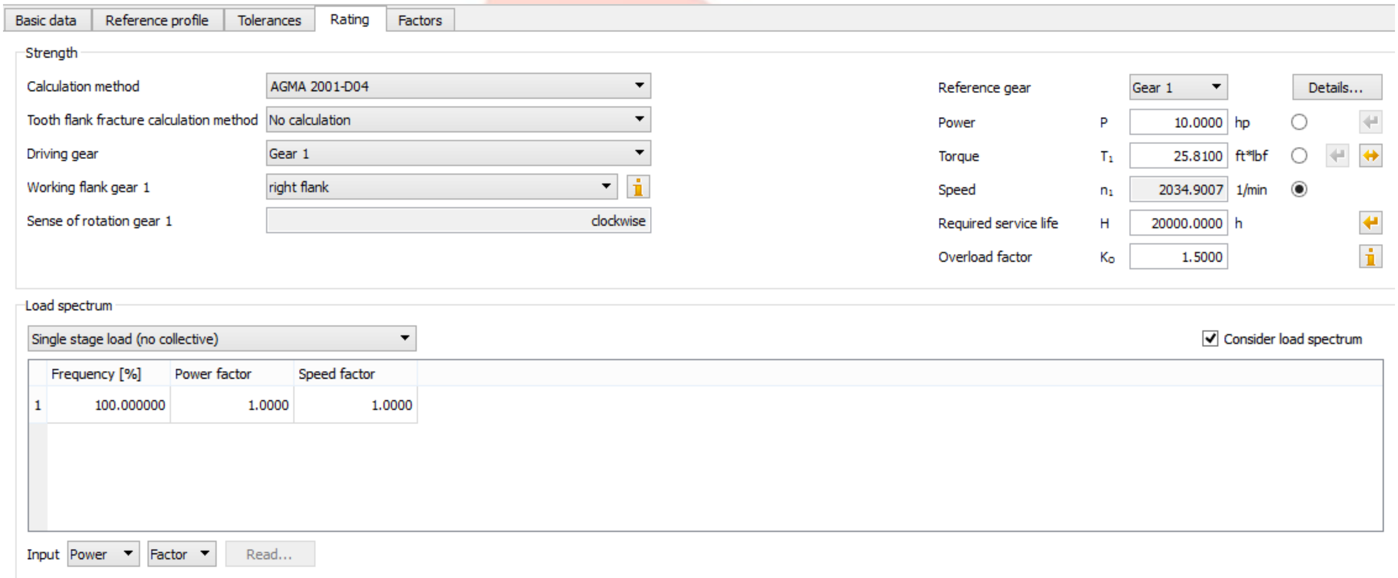

Fig.4 User interface of KISSsoft to input parameters

Various iterations have been done through the software of which some of the main iterations are listed below, out of which most optimum one have been selected.

Nr.	a [in]	b_1 [in]	b_2 [in]	P_{nd} [1/in]	β [°]	z_1	z_2	x^*_1	x^*_2	d_{a1} [in]	d_{a2} [in]	ε_α	ε_β	ε_γ	i	b/d_1	b/m_n
1	0.132	0.036	0.035	11.875	0.000	19	60	0.393	-0.021	0.072	0.205	1.525	0.000	1.525	3.158	0.553	10.500
2	0.183	0.024	0.022	10.841	0.000	24	76	0.349	0.021	0.097	0.283	1.594	0.000	1.594	3.167	0.250	6.001
3	0.113	0.052	0.050	11.754	0.000	16	51	0.429	-0.055	0.063	0.177	1.473	0.000	1.473	3.188	0.938	15.002
4	0.152	0.029	0.027	8.795	0.000	16	51	0.429	-0.055	0.084	0.237	1.473	0.000	1.473	3.188	0.375	6.001
5	0.133	0.041	0.040	14.853	0.000	24	76	0.349	0.021	0.071	0.207	1.593	0.000	1.593	3.167	0.625	15.000
6	0.131	0.037	0.035	12.000	0.000	19	60	0.398	0.002	0.071	0.203	1.520	0.000	1.520	3.158	0.569	10.809
7	2.950	1.276	1.231	12.000	0.000	17	54	0.354	-0.453	1.642	4.591	1.574	0.000	1.574	3.176	0.869	14.766
8	3.100	1.211	1.166	12.000	0.000	18	57	0.217	-0.507	1.701	4.831	1.650	0.000	1.650	3.167	0.777	13.987
9	3.300	1.015	0.972	14.000	0.000	22	69	0.433	0.306	1.771	5.110	1.504	0.000	1.504	3.136	0.619	13.614
10	3.300	1.114	1.071	14.000	0.000	22	70	0.337	-0.134	1.762	5.123	1.596	0.000	1.596	3.182	0.682	15.000
11	3.300	1.028	0.985	12.000	0.000	19	60	0.352	-0.251	1.809	5.125	1.572	0.000	1.572	3.158	0.622	11.821
12	3.450	0.960	0.917	14.000	0.000	23	72	0.448	0.401	1.843	5.336	1.498	0.000	1.498	3.130	0.558	12.841
13	3.450	1.043	1.000	14.000	0.000	23	73	0.346	-0.039	1.834	5.351	1.591	0.000	1.591	3.174	0.609	13.999
14	3.450	1.011	0.968	12.000	0.000	20	63	0.311	-0.410	1.885	5.348	1.619	0.000	1.619	3.150	0.581	11.616
15	3.450	0.887	0.844	10.000	0.000	16	51	0.549	0.553	1.889	5.390	1.333	0.000	1.333	3.188	0.528	8.445
16	3.600	0.973	0.930	14.000	0.000	24	76	0.357	0.055	1.906	5.578	1.586	0.000	1.586	3.167	0.543	13.020
17	3.600	0.989	0.946	12.000	0.000	21	66	0.272	-0.564	1.961	5.571	1.662	0.000	1.662	3.143	0.541	11.354
18	3.600	0.814	0.771	10.000	0.000	17	54	0.440	0.085	1.983	5.612	1.464	0.000	1.464	3.176	0.454	7.712
21	3.800	0.865	0.823	12.000	0.000	22	69	0.319	-0.218	2.053	5.880	1.613	0.000	1.613	3.136	0.449	9.871
22	3.800	0.926	0.883	12.000	0.000	22	70	0.149	-0.535	2.022	5.909	1.715	0.000	1.715	3.182	0.481	10.593
23	3.800	0.729	0.686	10.000	0.000	18	57	0.429	0.095	2.081	5.914	1.482	0.000	1.482	3.167	0.381	6.858
26	3.950	0.699	0.656	12.000	0.000	22	70	0.598	0.948	2.075	6.134	1.356	0.000	1.356	3.182	0.358	7.869
27	3.950	0.854	0.811	12.000	0.000	23	72	0.276	-0.376	2.129	6.104	1.656	0.000	1.656	3.130	0.423	9.737
28	3.950	0.888	0.845	12.000	0.000	23	73	0.011	-0.582	2.080	6.148	1.778	0.000	1.778	3.174	0.441	10.137
29	3.950	0.730	0.688	10.000	0.000	19	60	0.337	-0.337	2.167	6.133	1.589	0.000	1.589	3.158	0.362	6.876
33	4.100	0.694	0.651	12.000	0.000	23	73	0.541	0.763	2.156	6.360	1.416	0.000	1.416	3.174	0.340	7.815
34	4.100	0.951	0.908	12.000	0.000	24	76	-0.225	-0.524	2.121	6.404	1.857	0.000	1.857	3.167	0.454	10.892
35	4.100	0.722	0.680	10.000	0.000	20	63	0.064	-0.540	2.208	6.387	1.735	0.000	1.735	3.150	0.340	6.796
38	4.250	0.688	0.645	12.000	0.000	24	76	0.486	0.584	2.236	6.586	1.472	0.000	1.472	3.167	0.322	7.738
40	4.250	0.643	0.600	10.000	0.000	20	63	0.515	0.569	2.286	6.597	1.410	0.000	1.410	3.150	0.300	6.000

b/a	$SF_{smallest}$	$SH_{smallest}$	SB	SInt	Slam(B)	SFF_{min}(B)	SW_1	SW_2	$T_{1\,max}$ [ft*lbf]	P_{max} [hp]	η	W [lb]	H_{min} [h]
0.263	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	19.050	13.420	0.988	13.305	10155.662
0.119	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	19.042	13.414	0.992	15.822	10156.075
0.443	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	19.045	13.417	0.984	14.303	10104.398
0.177	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	19.038	13.412	0.987	13.732	10025.702
0.298	0.957	0.971	-1.000	-1.000	0.000	0.000	0.000	0.000	19.047	13.418	0.990	15.298	10332.572
0.271	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	19.022	13.400	0.988	13.287	9844.037
0.417	1.004	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	25.788	9.992	0.983	6.528	9820.803
0.376	1.013	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	25.797	9.995	0.984	6.821	9893.167
0.295	0.969	1.043	-1.000	-1.000	0.000	0.000	0.000	0.000	25.723	9.966	0.990	6.347	8274.679
0.325	0.962	1.067	-1.000	-1.000	0.000	0.000	0.000	0.000	25.540	9.895	0.988	7.006	5997.091
0.299	0.996	1.027	-1.000	-1.000	0.000	0.000	0.000	0.000	25.701	9.958	0.987	6.495	7891.430
0.266	0.975	1.066	-1.000	-1.000	0.000	0.000	0.000	0.000	25.893	10.032	0.991	6.526	11996.017
0.290	0.970	1.088	-1.000	-1.000	0.000	0.000	0.000	0.000	25.758	9.980	0.989	7.138	8927.125
0.281	0.998	1.061	-1.000	-1.000	0.000	0.000	0.000	0.000	25.747	9.976	0.987	6.949	8723.444
0.245	1.300	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	25.821	10.004	0.988	6.155	10092.534
0.258	0.968	1.103	-1.000	-1.000	0.000	0.000	0.000	0.000	25.704	9.959	0.990	7.213	7935.218
0.263	0.995	1.090	-1.000	-1.000	0.000	0.000	0.000	0.000	25.685	9.952	0.987	7.370	7624.736
0.214	1.114	1.001	-1.000	-1.000	0.000	0.000	0.000	0.000	25.836	10.010	0.988	6.107	10225.934
0.216	0.999	1.094	-1.000	-1.000	0.000	0.000	0.000	0.000	25.781	9.989	0.989	7.130	9386.863
0.232	0.998	1.082	-1.000	-1.000	0.000	0.000	0.000	0.000	25.763	9.982	0.988	7.687	9039.660
0.180	1.055	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	25.819	10.004	0.989	6.030	10080.148
0.166	1.000	1.030	-1.000	-1.000	0.000	0.000	0.000	0.000	25.813	10.001	0.992	6.149	10081.298
0.205	0.998	1.124	-1.000	-1.000	0.000	0.000	0.000	0.000	25.768	9.984	0.989	7.577	9139.619
0.214	0.998	1.070	-1.000	-1.000	0.000	0.000	0.000	0.000	25.759	9.980	0.989	7.948	8954.702
0.174	1.000	1.031	-1.000	-1.000	0.000	0.000	0.000	0.000	25.804	9.998	0.988	6.508	9870.395
0.159	1.000	1.067	-1.000	-1.000	0.000	0.000	0.000	0.000	25.807	9.999	0.992	6.570	9949.853
0.221	0.997	1.087	-1.000	-1.000	0.000	0.000	0.000	0.000	25.734	9.971	0.988	9.220	8482.420
0.166	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	25.799	9.996	0.988	6.942	9867.880
0.152	1.000	1.101	-1.000	-1.000	0.000	0.000	0.000	0.000	25.802	9.997	0.992	6.978	9831.197
0.141	1.177	1.076	-1.000	-1.000	0.000	0.000	0.000	0.000	29.900	11.585	0.991	6.742	129344.702

Fig.5 List of iterations for 1st stage reduction

V.II. For 2nd Stage Reduction

Input parameters

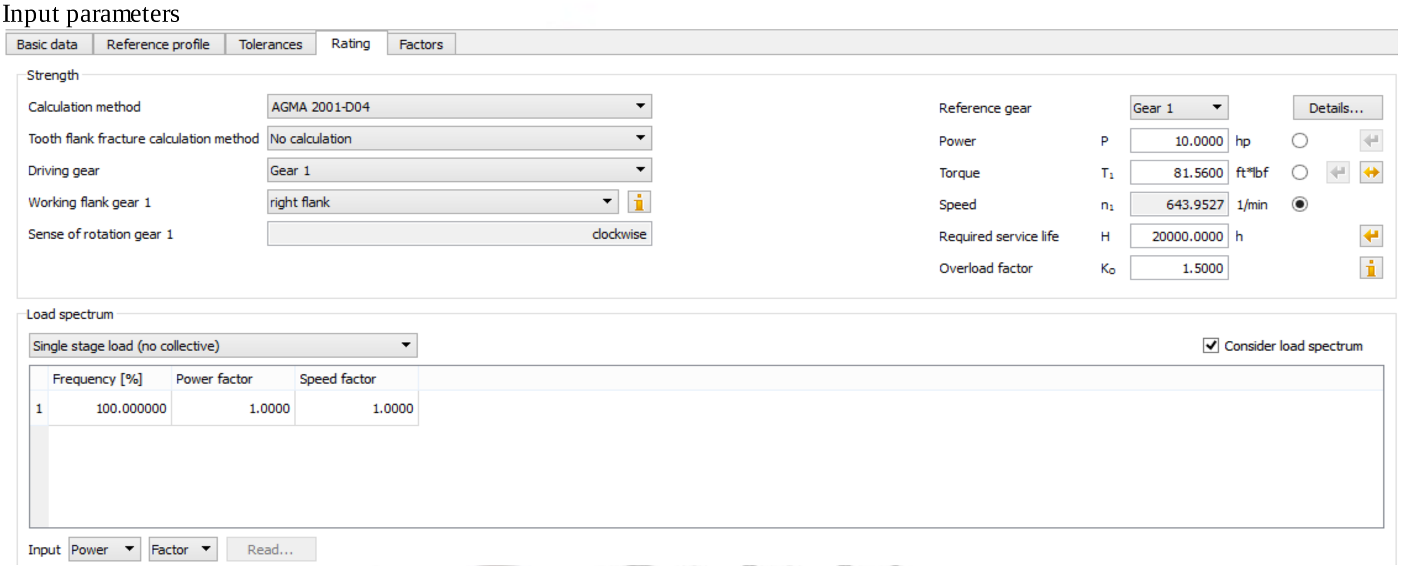

Fig.6 User interface of KISSsoft to input parameters

Nr.	a [in]	b_1 [in]	b_2 [in]	P_{nd} [1/in]	β [°]	z_1	z_2	x^*_1	x^*_2	d_{a1} [in]	d_{a2} [in]	$ε_α$	$ε_β$	$ε_γ$	i	b/d_1	b/m_n
1	0.169	0.047	0.044	9.304	0.000	19	60	0.393	-0.021	0.092	0.262	1.525	0.000	1.525	3.158	0.553	10.502
2	0.234	0.030	0.028	8.461	0.000	24	76	0.349	0.021	0.124	0.363	1.594	0.000	1.594	3.167	0.250	5.999
3	0.145	0.066	0.064	9.196	0.000	16	51	0.429	-0.055	0.081	0.226	1.473	0.000	1.473	3.188	0.938	15.000
4	0.193	0.037	0.034	6.891	0.000	16	51	0.429	-0.055	0.108	0.302	1.473	0.000	1.473	3.188	0.375	6.001
5	0.174	0.054	0.052	11.405	0.000	24	76	0.349	0.020	0.092	0.269	1.594	0.000	1.594	3.167	0.625	15.002
6	0.157	0.054	0.052	10.000	0.000	19	60	0.398	0.002	0.086	0.244	1.521	0.000	1.521	3.158	0.696	13.217
7	3.950	1.386	1.327	10.000	0.000	19	59	0.418	0.105	2.179	6.116	1.497	0.000	1.497	3.105	0.698	13.266
8	3.950	1.560	1.500	10.000	0.000	19	60	0.337	-0.337	2.167	6.133	1.589	0.000	1.589	3.158	0.789	15.000
10	4.150	1.300	1.241	10.000	0.000	20	62	0.408	0.114	2.277	6.418	1.513	0.000	1.513	3.100	0.620	12.406
11	4.150	1.457	1.397	10.000	0.000	20	63	0.325	-0.325	2.265	6.435	1.604	0.000	1.604	3.150	0.699	13.972
12	4.150	1.532	1.473	10.000	0.000	20	64	0.067	-0.543	2.209	6.487	1.734	0.000	1.734	3.200	0.736	14.727
13	4.150	1.280	1.220	8.000	0.000	16	50	0.404	-0.199	2.350	6.449	1.503	0.000	1.503	3.125	0.610	9.760
14	4.150	1.428	1.368	8.000	0.000	16	51	0.253	-0.542	2.311	6.487	1.619	0.000	1.619	3.188	0.684	10.946
15	4.400	1.231	1.171	10.000	0.000	21	66	0.400	0.121	2.376	6.820	1.529	0.000	1.529	3.143	0.558	11.709
16	4.400	1.365	1.305	10.000	0.000	21	67	0.315	-0.315	2.363	6.837	1.617	0.000	1.617	3.190	0.621	13.050
17	4.400	1.122	1.062	8.000	0.000	17	53	0.390	-0.186	2.471	6.828	1.522	0.000	1.522	3.118	0.500	8.498
18	4.400	1.249	1.189	8.000	0.000	17	54	0.234	-0.524	2.431	6.867	1.636	0.000	1.636	3.176	0.560	9.512
19	4.600	1.170	1.110	10.000	0.000	22	69	0.392	0.128	2.474	7.122	1.543	0.000	1.543	3.136	0.505	11.100
20	4.600	1.282	1.222	10.000	0.000	22	70	0.304	-0.304	2.461	7.139	1.630	0.000	1.630	3.182	0.556	12.223
21	4.600	1.034	0.974	8.000	0.000	17	54	0.612	0.849	2.488	7.172	1.282	0.000	1.282	3.176	0.458	7.791
22	4.600	1.100	1.040	8.000	0.000	18	56	0.324	-0.520	2.580	7.119	1.607	0.000	1.607	3.111	0.462	8.323
23	4.600	1.045	0.985	7.200	0.000	16	50	0.393	-0.271	2.609	7.146	1.518	0.000	1.518	3.125	0.443	7.095
24	4.600	1.223	1.163	7.200	0.000	16	51	0.148	-0.511	2.536	7.215	1.661	0.000	1.661	3.188	0.523	8.374
25	4.800	1.113	1.054	10.000	0.000	23	72	0.384	0.135	2.573	7.423	1.556	0.000	1.556	3.130	0.458	10.537
26	4.800	1.214	1.154	10.000	0.000	23	73	0.294	-0.294	2.559	7.441	1.641	0.000	1.641	3.174	0.502	11.543
27	4.800	1.278	1.218	10.000	0.000	23	74	0.025	-0.505	2.501	7.495	1.764	0.000	1.764	3.217	0.530	12.181
28	4.800	0.923	0.864	8.000	0.000	18	56	0.632	0.946	2.613	7.442	1.275	0.000	1.275	3.111	0.384	6.908
29	4.800	0.945	0.885	8.000	0.000	18	57	0.509	0.467	2.608	7.473	1.397	0.000	1.397	3.167	0.394	7.083
30	4.800	0.977	0.917	8.000	0.000	18	58	0.413	0.003	2.599	7.497	1.503	0.000	1.503	3.222	0.408	7.337
31	4.800	1.151	1.091	8.000	0.000	19	59	-0.030	-0.533	2.608	7.483	1.767	0.000	1.767	3.105	0.459	8.730
32	4.800	0.965	0.905	7.200	0.000	16	51	0.563	0.612	2.625	7.499	1.319	0.000	1.319	3.188	0.407	6.515
33	4.800	1.093	1.033	7.200	0.000	17	53	0.120	-0.538	2.666	7.483	1.688	0.000	1.688	3.118	0.438	7.438
34	5.000	1.066	1.006	10.000	0.000	24	75	0.376	0.142	2.672	7.725	1.568	0.000	1.568	3.125	0.419	10.061
35	5.000	1.157	1.098	10.000	0.000	24	76	0.284	-0.284	2.657	7.743	1.652	0.000	1.652	3.167	0.457	10.976
36	5.000	1.233	1.173	10.000	0.000	24	77	0.113	-0.593	2.619	7.777	1.748	0.000	1.748	3.208	0.489	11.731
37	5.000	0.849	0.790	8.000	0.000	19	59	0.524	0.566	2.734	7.744	1.391	0.000	1.391	3.105	0.332	6.316
38	5.000	0.879	0.819	8.000	0.000	19	60	0.419	0.104	2.724	7.770	1.499	0.000	1.499	3.158	0.345	6.552
39	5.000	0.976	0.916	8.000	0.000	19	61	0.340	-0.340	2.710	7.790	1.590	0.000	1.590	3.211	0.386	7.331
40	5.000	0.893	0.833	7.200	0.000	17	53	0.541	0.558	2.762	7.766	1.352	0.000	1.352	3.118	0.353	6.000
41	5.000	0.893	0.833	7.200	0.000	17	54	0.440	0.085	2.754	7.795	1.464	0.000	1.464	3.176	0.353	6.000
45	5.200	0.816	0.759	8.000	0.000	20	62	0.428	0.204	2.849	8.043	1.494	0.000	1.494	3.100	0.304	6.075
46	5.200	0.901	0.845	8.000	0.000	20	63	0.340	-0.239	2.835	8.065	1.587	0.000	1.587	3.150	0.338	6.757
47	5.200	0.969	0.913	8.000	0.000	20	64	0.177	-0.562	2.791	8.106	1.693	0.000	1.693	3.200	0.365	7.304

b/a	$SF_{smallest}$	$SH_{smallest}$	SB	SInt	Slam(B)	$SFF_{min}(B)$	SW_1	SW_2	$T_{1\,max}$ [ft*lbf]	P_{max} [hp]	η	W [lb]	H_{min} [h]
0.263	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.124	13.403	0.987	27.666	19778.906
0.119	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.145	13.408	0.991	33.272	19822.158
0.443	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.138	13.406	0.983	29.859	19882.549
0.177	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.207	13.422	0.985	28.552	20386.241
0.298	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.148	13.409	0.989	33.790	19862.343
0.331	1.000	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	60.104	13.399	0.986	28.049	19637.537
0.336	1.002	1.005	-1.000	-1.000	0.000	0.000	0.000	0.000	81.740	10.022	0.987	12.489	22654.121
0.380	0.992	1.033	-1.000	-1.000	0.000	0.000	0.000	0.000	80.872	9.916	0.985	14.052	18455.813
0.299	0.999	1.027	-1.000	-1.000	0.000	0.000	0.000	0.000	81.451	9.987	0.988	12.853	18565.549
0.337	0.999	1.059	-1.000	-1.000	0.000	0.000	0.000	0.000	81.483	9.991	0.986	14.515	18976.098
0.355	0.999	1.007	-1.000	-1.000	0.000	0.000	0.000	0.000	81.445	9.986	0.985	15.428	18490.062
0.294	1.118	1.001	-1.000	-1.000	0.000	0.000	0.000	0.000	81.790	10.028	0.984	12.844	21273.063
0.330	1.117	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.497	9.992	0.982	14.486	19673.863
0.266	1.000	1.054	-1.000	-1.000	0.000	0.000	0.000	0.000	81.600	10.005	0.988	13.642	20575.257
0.297	0.999	1.082	-1.000	-1.000	0.000	0.000	0.000	0.000	81.482	9.990	0.987	15.247	18966.154
0.241	1.060	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.612	10.006	0.985	12.524	20285.857
0.270	1.067	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.595	10.004	0.984	14.096	20196.402
0.241	1.002	1.078	-1.000	-1.000	0.000	0.000	0.000	0.000	81.754	10.024	0.989	14.098	22866.424
0.266	0.996	1.102	-1.000	-1.000	0.000	0.000	0.000	0.000	81.200	9.956	0.988	15.567	15609.903
0.212	1.267	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.566	10.001	0.989	12.551	20038.772
0.226	1.004	1.023	-1.000	-1.000	0.000	0.000	0.000	0.000	81.855	10.036	0.985	13.340	24512.432
0.214	1.110	1.002	-1.000	-1.000	0.000	0.000	0.000	0.000	81.952	10.048	0.984	12.760	22205.907
0.253	1.215	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.496	9.992	0.983	15.196	19667.900
0.220	0.999	1.098	-1.000	-1.000	0.000	0.000	0.000	0.000	81.440	9.985	0.990	14.537	18420.399
0.240	0.996	1.123	-1.000	-1.000	0.000	0.000	0.000	0.000	81.247	9.962	0.989	15.966	16120.810
0.254	0.999	1.076	-1.000	-1.000	0.000	0.000	0.000	0.000	81.516	9.995	0.988	16.978	19415.811
0.180	1.208	1.001	-1.000	-1.000	0.000	0.000	0.000	0.000	81.658	10.012	0.990	12.026	20536.210
0.184	1.119	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.639	10.010	0.988	12.414	20434.288
0.191	1.032	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.609	10.006	0.987	12.919	20272.932
0.227	1.085	0.999	-1.000	-1.000	0.000	0.000	0.000	0.000	81.372	9.977	0.985	15.313	19031.410
0.189	1.314	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.621	10.007	0.988	12.782	20333.952
0.215	1.154	0.999	-1.000	-1.000	0.000	0.000	0.000	0.000	81.476	9.990	0.984	14.579	19563.442
0.201	0.998	1.120	-1.000	-1.000	0.000	0.000	0.000	0.000	81.420	9.983	0.990	15.029	18167.724
0.220	0.996	1.143	-1.000	-1.000	0.000	0.000	0.000	0.000	81.259	9.963	0.989	16.435	16252.379
0.235	1.000	1.129	-1.000	-1.000	0.000	0.000	0.000	0.000	81.549	9.999	0.988	17.643	19860.584
0.158	1.075	1.000	-1.000	-1.000	0.000	0.000	0.000	0.000	81.620	10.007	0.989	11.929	20328.926
0.164	1.000	1.001	-1.000	-1.000	0.000	0.000	0.000	0.000	81.595	10.004	0.988	12.436	20496.309
0.183	0.999	1.034	-1.000	-1.000	0.000	0.000	0.000	0.000	81.508	9.994	0.986	13.946	19311.255
0.167	1.300	1.033	-1.000	-1.000	0.000	0.000	0.000	0.000	87.088	10.678	0.989	13.038	45549.880
0.167	1.149	1.017	-1.000	-1.000	0.000	0.000	0.000	0.000	84.326	10.339	0.987	13.113	22602.070
0.146	1.001	1.018	-1.000	-1.000	0.000	0.000	0.000	0.000	81.621	10.007	0.989	12.383	20866.757
0.162	1.000	1.050	-1.000	-1.000	0.000	0.000	0.000	0.000	81.545	9.998	0.988	13.814	19807.910
0.176	0.999	1.038	-1.000	-1.000	0.000	0.000	0.000	0.000	81.483	9.991	0.987	15.005	18970.871

Fig.7 List of iterations for 2^{nd} stage reduction

V.III. For Input shaft

The diameter of shaft have been optimized on the basis of strength and deflection.

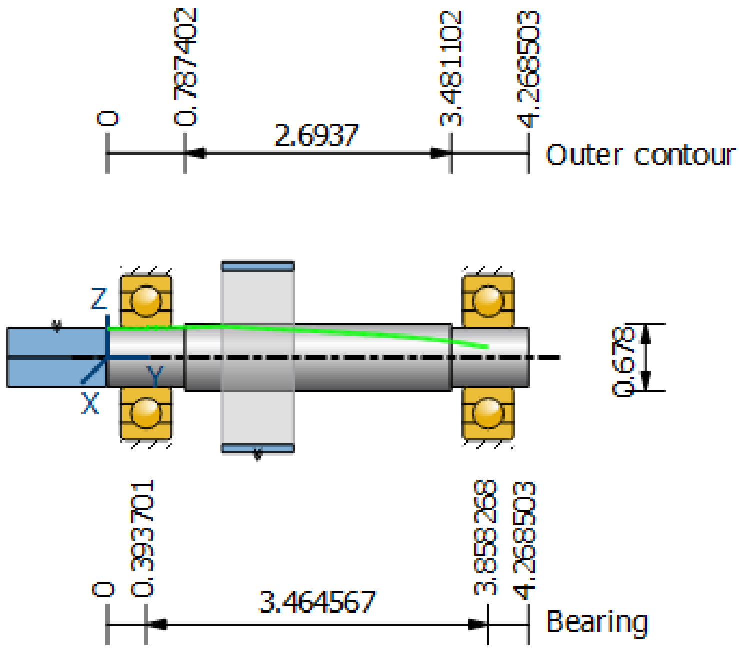

Fig.8 Optimized input shaft

V.IV. For Intermediate Shaft

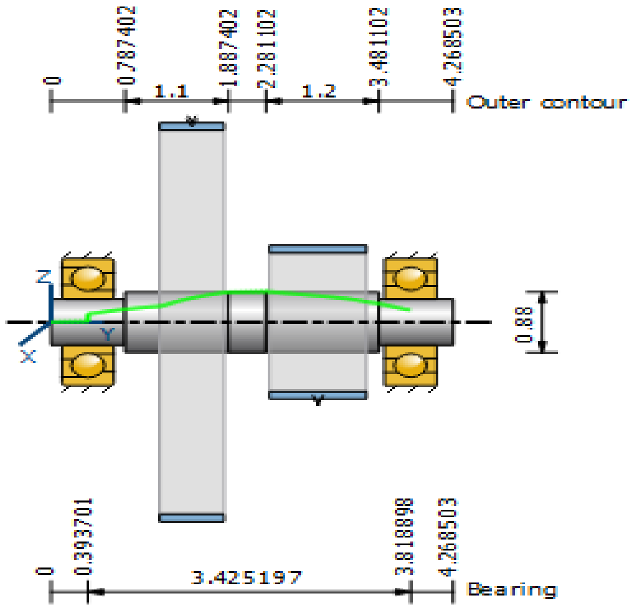

Fig.9 Optimized intermediate shaft

V.V. For Output Shaft

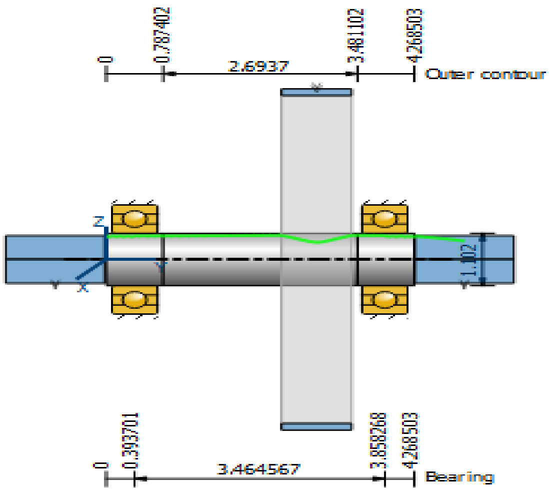

Fig.10 Optimized output shaft

VI. RESULT AND CONCLUSION

The comparative study of the solutions shown in Table 3 leads to the following conclusions:

- The volume of the all gears and shafts calculated with the classical method is 99.3788 cu.in, while the optimal design solution offers a smaller volume, equal to 68.069 cu.in. i.e. a 31.503% reduction.

- The optimal design solution has the transmission ratio for the first stage almost equal to the second stage. That confirms the recommendations found in literature.

Table 3 Classical and optimal design solutions

No.	Classical solution	Optimal Solution	Denotation
Main characteristic of the first stage			
1	Transmission ratio		
	3.16	3.167	i
2	Centre working distance(inch)		
	4.4096	3.8	a_w
3	Module (inch)		
	0.1181	0.1	m_n
4	Number of teeth of the pinion		
	18	18	Z_1
5	Number of teeth of the wheel		
	57	57	Z_2
6	Pitch diameters(inch)		
	2.12	1.824	D_1
	6.69	5.776	D_2
7	Face Width(inch)		
	1.181	0.729	F_1
	1.181	0.686	F_2

Table 4 Classical and optimal design solutions

No.	Classical solution	Optimal Solution	Denotation
Main characteristic of the second stage			
1	Transmission ratio		
	3.16	3.176	i
2	Centre working distance(inch)		
	4.4096	4.610	a_w
3	Module(inch)		
	0.1181	0.125	m_n
4	Number of teeth of the pinion		
	18	17	Z_3
5	Number of teeth of the wheel		
	57	54	Z_4
6	Pitch diameters(inch)		
	2.12	2.207	D_3
	6.69	7.012	D_4
7	Face Width(inch)		
	1.4835	1.034	F_3
	1.4835	0.974	F_4

Table 5 Classical and optimal design solutions

No.	Classical solution	Optimal solution
Main characteristic of Input Shaft		
1	Main diameter(inch)	
	0.6368	0.678
2	Shoulder diameter(inch)	
	0.6368	0.591
3	Length(inch)	
	4.633	4.268

Table 6 Classical and optimal design solutions

No.	Classical solution	Optimal solution
Main characteristic of Intermediate Shaft		
1	Main diameter(inch)	
	0.875	0.875
2	Shoulder diameter(inch)	
	1.125	0.669
3	Length(inch)	
	4.633	4.268

Table 7 Classical and optimal design solutions

No.	Classical solution	Optimal solution
Main characteristic of Output Shaft		
1	Main diameter(inch)	
	1.128	1.100
2	Shoulder diameter(inch)	
	1.128	1.102
3	Length(inch)	
	4.633	4.268

VII. REFERENCES

1. Optimal design of two-stage speed reducer, LUCIAN TUDOSE, OVIDIU BUIGA, DANIELA JUCAN, CORNEL STEFANACHE, ISBN: 978-960-474-019-2, ISSN: 1790-2769, MACMESE'08.
2. Shigley S Mechanical Engineering Design 8th Edition, Pg.349-943.
3. Design of Machine Elements, V.B.Bhandari-2010,Pg 330, 646.
4. KISSsoft Software, Copyright 1998-2015, KISSsoft AG, Rosengartenstrasse 4, CH-8608 Bubikon.
5. Budynas−Nisbett: "Shigley's Mechanical Engineering Design", Eighth Edition, 2008; Pg. 746-47
6. Gitin M. Maitra:" Handbook of gear design", 1994
7. Stephen P. Radzevich; "Dudley's Handbook of Practical Gear Design and Manufacture", Second Edition, 2012
8. Kapelevich, A. and McNamara, T., "Direct Gear Design® for Automotive Applications", 2013
9. Milosav Ognjanovic1 – Miroslav Milutinovic2," Design for Reliability Based Methodology For Automotive Gearbox Load Capacity Identification", 2012
10. Wikipedia