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Structural analysis of a cylindrical gear in the ANSYS program

T M Ştefănescu, O N Volintiru, I C Scurtu
[1]Romanian Navy

Abstract. Among most military ships, the use of a performing marine gearbox is mandatory due to their propulsion systems based on gas turbines in most cases. Military vessels are navigating under different conditions and this determines different operating modes for the propulsion system, thus the main gearing. Each of this operating mode determines different types of stress and deformation values upon the gears inside the main gearing. The purpose of this paper is the simplified gear analysis inside the gearbox using the Ansys program related to different operating modes of the propulsion system.

Keywords: type 22 frigate, operating mode, moment of torsion.

1. Introduction. Main gearbox of a type 22 frigate

The main gearing inside the main gearbox of a type 22 frigate (Figure 1.a) is a double helical, double reduction, dual tandem, articulated locked train arrangement using carburized gears (Figure 1.b). The common input primary pinion (1) meshes with two primary wheels (2) located on either side of it. Each primary wheel is connected to a secondary pinion (3) through a quill shaft (4) and each secondary pinion meshes with the main wheel (5). The propeller shaft (6) is driven by the main wheel through the thrust block (7).

The gas turbines transmit power to the gearbox via a common shaft. Between each gas turbine (main turbine output is 8 and cruising turbine output is 9) and the primary pinion are Synchro-Self-Shifting clutches (10). These clutches are automatic and connect the driving engine to the gearing and disconnect the non-driving engine.

Incorporated in the gearing is an air operated shaft brake (11). This consists of friction pads placed on either side of a disc mounted on an extension stub shaft bolted to the upper secondary pinion shaft (similar to a car disc brake assembly). Introduction of air pressure behind the friction pads brings them into contact with the disc.

Reduction ratio:

- Primary: 4.135 to 1
- Secondary: 5.22 to 1
- Overall: 21.59 to 1

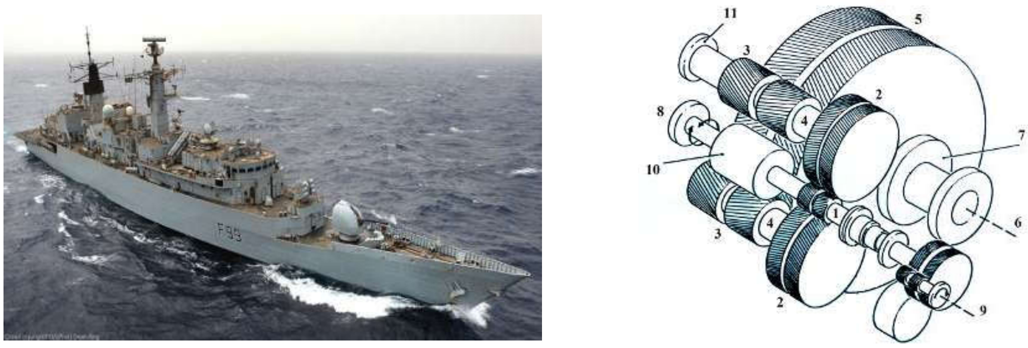


Figure 1.a Type 22 frigate Figure 1.b Main gearing

Figure 1 Introduction to a type 22 frigate and her main gearing

2. Geometric parameters of the calculation model

In order to analyze the behavior of the main gearbox of a type 22 frigate while working under particular conditions, it will be considered the model of a simplified gear in the Ansys 19 Student computer program. The purpose of the simulation is to determine the equivalent stress (von-Mises) and total deformation at the contact point between the teeth of two opposite wheels. For the simplicity of the simulation, it will be considered a cylindrical gear formed by two simple toothed wheels, according to figure 2, on which the load study will be done by the finite element analysis method.

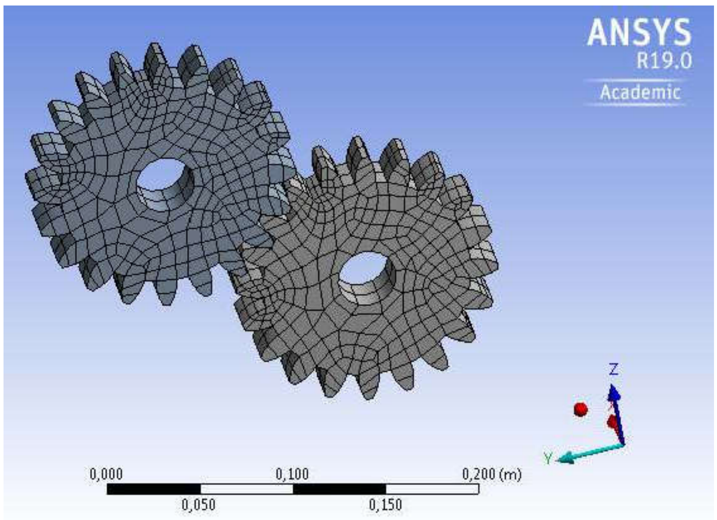


Figure 2 Simple gear scaled model meshed in Ansys 19 Student

In Table 1 there are five operating modes for the main turbine of a type 22 frigate, which lead to five different gearing load conditions.

Table 1. Main Gas Turbine Parameters for five different operating modes.

Operating mode	PCL [%]	Fuel Consumption $\left[\frac{l}{min}\right]$	Main shaft speed [rpm]	Oil pressure [bar]	LP Compressor speed [rpm]	Gas Turbine Exhaust Temp [^{0}C]	Power Turbine Speed [rpm]	Fuel Pressure [bar]
1	82	82,2	184	3,2	6500	510	3700	1,8
2	75	65,3	171	3,2	6100	500	3400	1,8
3	61	35,1	134	3,2	5100	440	2700	1,5
4	40	34,2	86	2,9	3900	240	1800	1,3
5	16	13,6	52	2,8	2000	250	1000	1,2

The five operating modes shown in Table 1 are frequently encountered during the operation of military ships, such as: the march to a designated point (1), the replenishment at sea maneuver (2), the helicopter landing maneuver (3), and the mooring/departure to/from pier (4) and (5) (for example).

The helmsman, by means of PCLs (Power Control Lever), sets the percentage of the maximum power of the turbines to be delivered to the propeller shaft, thus determining the speed of the ship. The main turbine of a type 22 frigate is a Rolls Royce Olympus TM3B with a maximum power output of 18802,242 [KW] coupled to the main gearbox of the ship. According to the calculation relations (1) ... (8), only 5000 [kW] will be returned from the total power of the power turbine that drives the shaft through the main gearbox.

The most common used naval Diesel fuel has the following concentration:

$c = 85{,}6$ % (carbon)
$h = 13$ % (hydrogen)
$s = 1{,}08$ % (sulfur)
$o = 0{,}01$ % (oxygen)
$n = 0{,}29$ % (nitrogen)
$a = 0{,}02$ % (other compounds)

The amount of air required to burn one kilogram of fuel will be:

$$m_{air} = \frac{\frac{8}{3}*c+8*h+s-o}{23{,}2}\left[\frac{Kgair}{Kgfuel}\right] \quad (1)$$

$$m_{air} = 14{,}35\left[\frac{Kgaer}{Kgfuel}\right] \quad (2)$$

As shown in figure 3, the input functional parameters for temperature and pressure of the gas turbine installation are T_1=318 [K] (the temperature within the machinery compartment) and p_1=17 [bar] (the input air pressure). Also, for this specific installation (Rolls Royce Olympus TM3B) it is known the hourly fuel consumption as being 5000 $\left[\frac{Kgfuel}{h}\right]$ and the fact that the energy flow is the one indicated by the arrows.

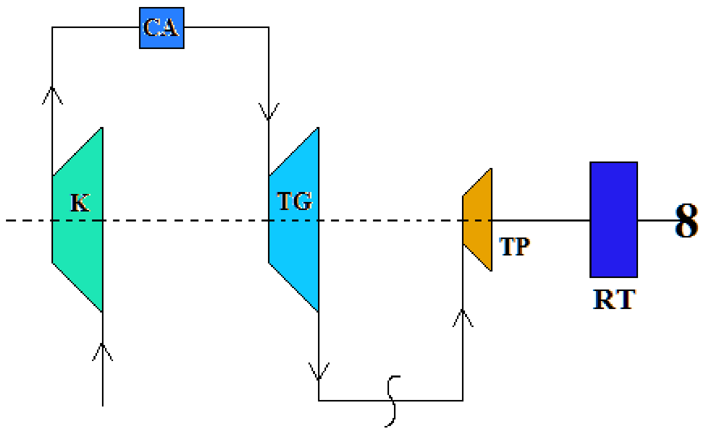


Figure 3 Diagram of the type 22 frigate main gas turbine plant

where **K** is the air compressor, **CA** is the combustion chamber, **TG** is the gas generator and **TP** is the power turbine.

The second purpose of this paragraph is to prove that from the total power of one given gas turbine plant only one fraction of it is actually used for training the propeller shaft (via the gearbox).

The output temperature from the **K** compressor will be:

$$T = 318 \cdot 17^{0,26} = 664,268 \ [K] \tag{3}$$

It is considered that the value of the coefficient of excess air α (between 1,5 and 1,8) is 1,7. Taking into account the (6) result and the hourly fuel consumption will be:

$$\dot{m}_{air} = c_h \cdot \frac{1}{3600} \cdot \alpha \cdot m_{air} \tag{4}$$

$$\dot{m}_{air} = 33,881 \left[\frac{Kgair}{s}\right] \tag{5}$$

The airflow received by the compressor or the training power of the compressor will be:

$$\dot{Q}_{airK} = \dot{m}_{air} \cdot c_{air} \cdot (T - T_0) \tag{6}$$

Where c_{air} is the specific heat of air. The (10) formulae gets:

$$\dot{Q}_{airK} = 33,881 \cdot 1 \cdot (664,268 - 318) = 11731,906 \ [kW] \tag{7}$$

Taking into account the frictional losses and considering the air compressor's efficiency as 0,85 the power from the gas turbine plant will be:

$$\dot{Q}_{TG} = \frac{\dot{Q}_{aerK}}{\eta_K} = \frac{11731,906}{0,85} = 13802,242 \ [kW] \tag{8}$$

So, of the total power generated by the 18802,242 [kW] turbine power plant, the power turbine that drives the main shaft through the main gearbox will return the power of 5000 [kW].

3. Performing the simulation on the chosen model

Table 2 describes five different operating modes for the main turbine that leads to five different values for the output power of the power turbine, input and output shaft speeds.

Table 2. Working parameters of the propulsion system according to five different operating modes.

Operating mode	PCL [%]	Output power P_1 [KW]	Power turbine speed n_1 [rpm]	Main shaft speed n_2 [rpm]
1	82	4100	3700	180
2	75	3750	3400	164
3	61	3050	2700	134
4	40	2000	1800	87
5	16	800	1000	52

The moment of torsion for the input pinion is

$$M_{t1} = \frac{P_1}{\omega_1}\ [KNm] \tag{9}$$

The moment of torsion for the output pinion is

$$M_{t2} = \frac{P_2}{\omega_2}\ [KNm] \tag{10}$$

P_1 and P_2 are the output power of the main Gas Turbine, respectively the output power for the gearbox.

$$P_2 = \eta_{gearbox} P_1\ [KW] \tag{11}$$

$$\eta_{gearbox} = 0{,}94 \dots 0{,}98\ [-] \tag{12}$$

$\eta_{gearbox}$ represents the output power loss due to the moving elements of the main gearbox
ω_1 and ω_2 are the angular speed for the input respectively the output pinion.

$$\omega_{1,2} = \frac{2\pi n_{1,2}}{60}\ [rpm] \tag{13}$$

n_1 and n_2 are the speeds of the input, respectively the output shaft.

For simplicity of the calculus, it is taken into account a single stage reduction.

It is known that

$$\frac{M_{t1}}{M_{t2}} = \frac{1}{\eta_{gearbox}} \frac{n_2}{n_1} \tag{14}$$

Therefore

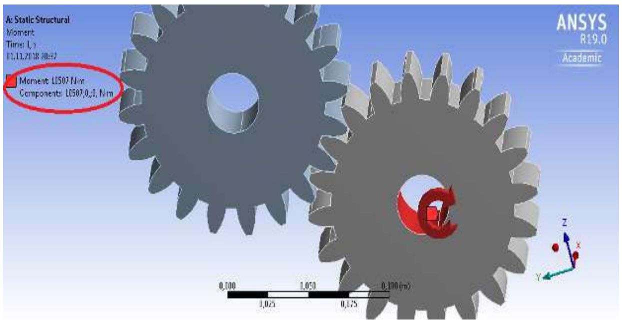
$$M_{t2} = \eta_{gearbox} M_{t1} \frac{n_1}{n_2}\ [KNm] \tag{15}$$

Applying the (15) formulae for the numerical values in table 1, the following results will follow such as in table 3:

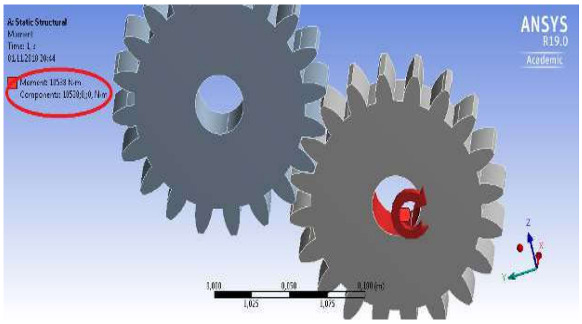
Table 3. Moment of torsion for input pinion and output wheel according to five different operating modes.

Operating mode	Moment of torsion for the input pinion M_{t1} [KNm]	Moment of torsion for the output wheel M_{t2} [KNm]
1	10,587	204,565…213,270
2	10,538	205,356…214,094
3	10,793	204,416…213,114
4	10,616	206,457…215,243
5	7,643	138,168…144,047

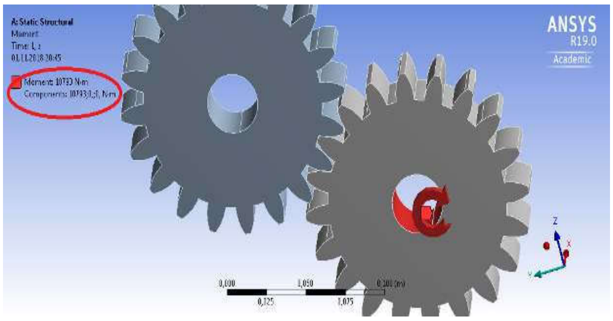
In the following, the moment of torsion M_{t1} of the input pinion will be applied, with the values in table 3, second column (figure 4).



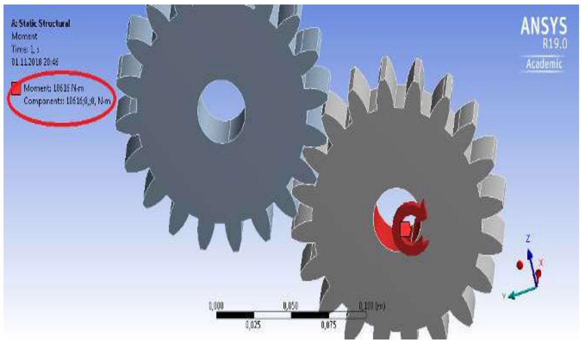
Operating mode 1



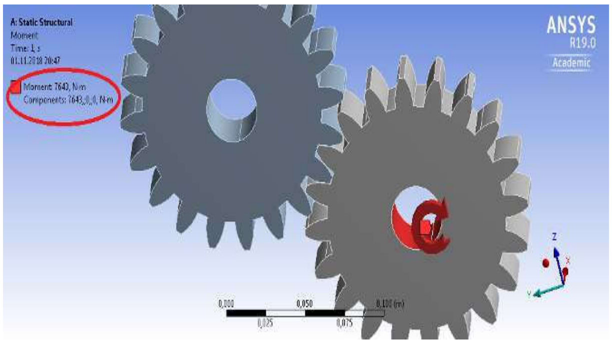
Operating mode 2



Operating mode 3



Operating mode 4



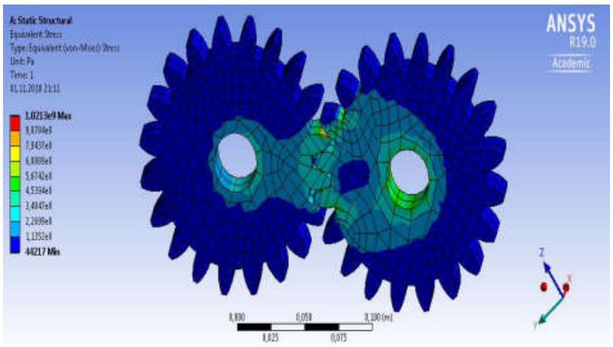
Operating mode 5

Figure 4 Applying the moment of torsion to the input pinion

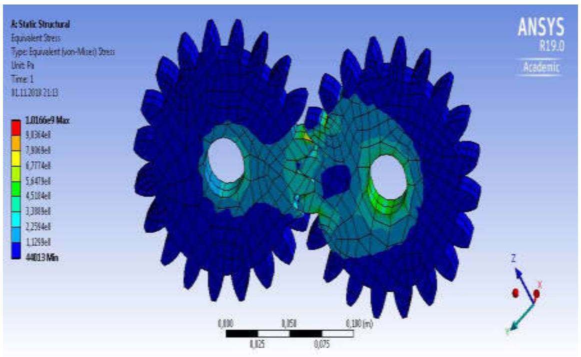
4. Interpretation of simulation results

For the geometric model of the scaled gear generated model with the successive application of the moments of torsion on the input pinion calculated in Table 3, the second column, the following results were obtained (it will be taken into account that in each printscreen the pinion on which the moment of torsion is applied is the one on the right):

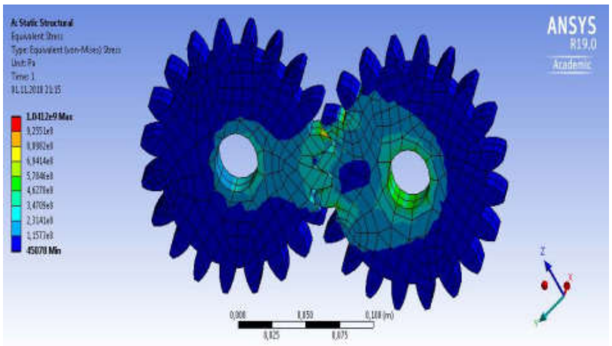
a) Equivalent stress (von-Mises):



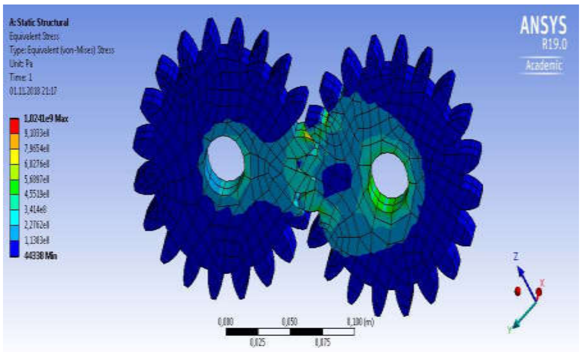
Operating mode 1



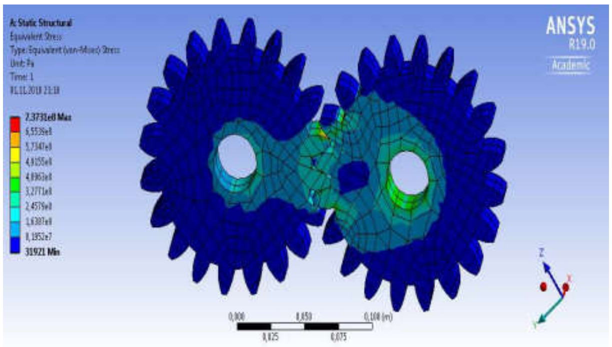
Operating mode 2



Operating mode 3



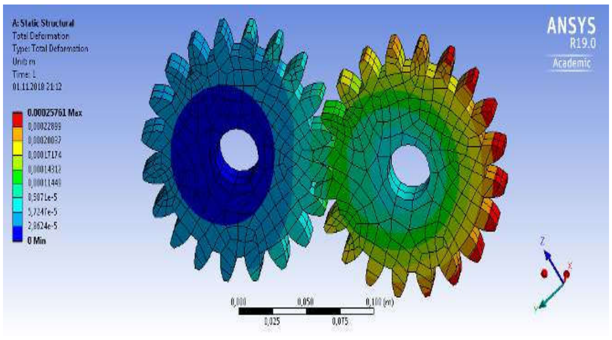
Operating mode 4



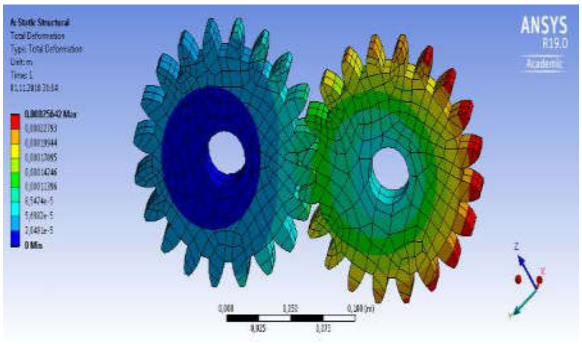
Operating mode 5

Figure 5 Equivalent stress values (von-Mises) for the five operating modes

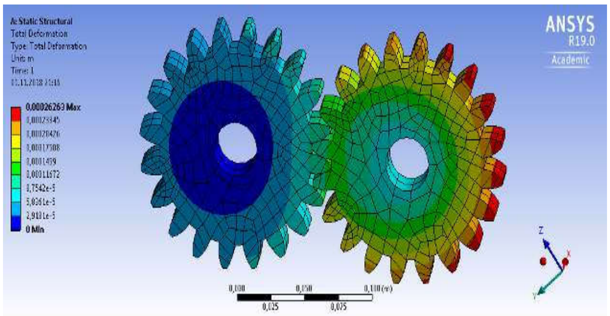
b) Total deformation value:



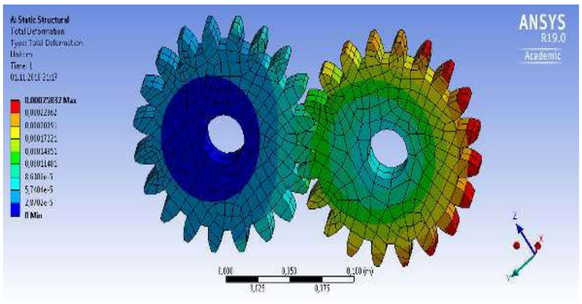
Operating mode 1



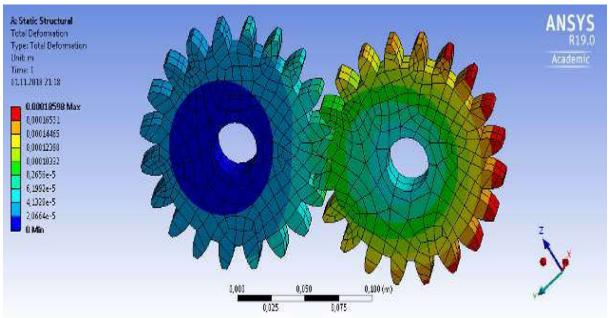
Operating mode 2



Operating mode 3



Operating mode 4



Operating mode 5

Figure 6 Total deformation values for the five operating modes

It is obvious that the structure of the equivalent stresses (von-Mises) and the structure of the total deformations are identical in all five operating modes. The value by which each tooth suffers the deformation pattern depends on the torque value M_{t1}.

A geometric model with 6504 knots and 976 construction elements was used for this simulation. The temporary simulation factor is 10 ms.

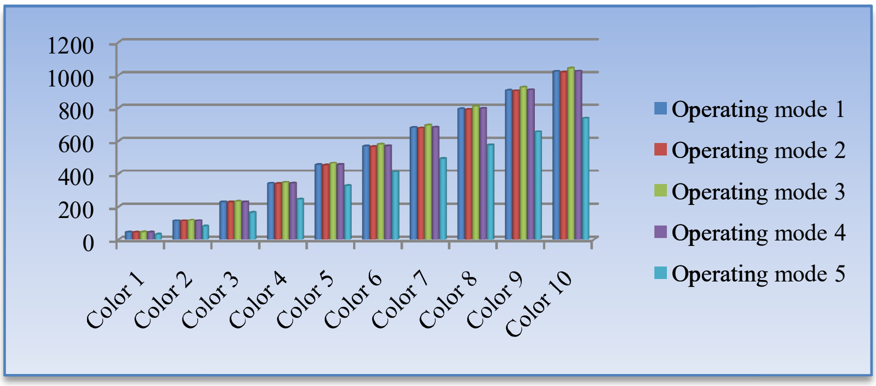
The unit of measurement for the results in Table 4 was considered to be kPa, and for Table 5 it was considered as the micron. The time unit was considered to be a millisecond for both tables. The total duration of the simulation for which the torsion moments in table 3, second column, were applied was 10 milliseconds, each millisecond being represented by one color.

Table 4. Interpretation of results for equivalent stress values (von-Mises).

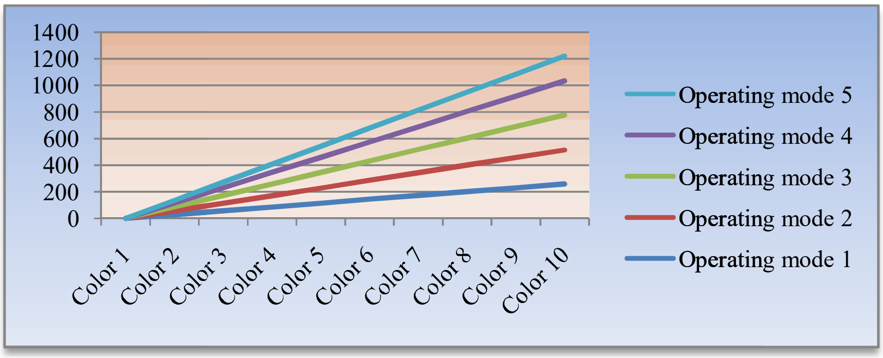
Operating mode										
1	44,217	113,52	226,99	340,47	453,94	567,42	680,89	794,37	907,84	1021,3
2	44,013	112,99	225,94	338,89	451,84	564,79	677,74	790,69	903,64	1016,6
3	45,078	115,73	231,41	347,09	462,78	578,46	694,14	809,82	925,51	1041,2
4	44,338	113,83	227,62	341,4	455,19	568,97	682,76	796,54	910,33	1024,1
5	31,921	81,952	163,87	245,79	327,71	409,63	491,55	573,47	655,39	737,31

Table 5. Interpretation of results for total deformation values.

Operating mode										
1	0	28,62	57,24	85,87	114,49	143,12	171,74	200,37	228,99	257,61
2	0	28,49	56,98	85,47	113,96	142,46	170,95	199,44	227,93	256,42
3	0	29,18	58,36	87,54	116,72	145,9	175,08	204,26	233,45	262,63
4	0	28,7	57,4	86,1	114,81	143,51	172,21	200,91	229,62	258,32
5	0	20,66	41,32	64,99	82,65	103,32	123,98	144,65	165,31	185,98



7.a. Interpretation of results for equivalent stress values (von-Mises)



7.b. Interpretation of results for total deformation values

Figure 7 Graphical interpretation of results

The geometrically chosen model on which the moment of torsion M_{t1} is applied with the values in Table 3, the second column is approximated as a mode of behavior with a real gear. This simulation method can reduce the cost of testing for actual gears. Conclusions (Figure 7) provide relevant values for gearbox optimization from the main gearbox used for military ships with combined propulsion systems comprising gas turbines.

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