Topography Optimization of an Aircraft Engine Gearbox

Nuz Wattananaphakaseam, Natthasit Sittisang, Napat Phengsalae and Daniele Dipasquale

Department of Aeronautical Engineering, International Academy of Aviation Industry, King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand

1 E-mail: daniele.di@kmtil.ac.th

Abstract. Topography Optimization (TO) is a mathematical method extensively employed to optimize material layout within the design space, for a given set of boundary conditions with the goal of maximizing the performance of the system. This process takes a three-dimensional design space and whittles material away within it to achieve the most efficient design. Currently, engineers use this mathematical approach at a concept level of a design process, leading to results which are often fine-tuned for manufacturability. In some cases, the optimized geometry can be directly manufactured using additive manufacturing, indeed, TO is a key part of design for additive manufacturing. This work aims to apply TO in order to minimize the mass of an engine gearbox while maintaining an acceptable mechanical performance when compared to the original design. Numerical simulations are carried out by means of CAD and FEM software to improve the design of an aircraft gearbox composed of four gears, therefore, irrelevant parts of material are removed in the design space to meet the goal of minimizing the mass of the gearbox. The application of TO allows to obtain a better, lighter, and more efficient design of the gearbox by keeping its mechanical performance unchanged.

1. Introduction

In a coaxial aircraft gearbox, gears play an essential role in transmitting the mechanical power [1]. These gears operating under high torques are designed to withstand stress and forces acting on them while operating [1]. Gears are the most common means of transmitting power [2]. In this aeronautical case, it also changes the rate of rotation of the machinery shaft and the axis of rotation [2]. While traditional gears are designed to withstand a certain amount of load, designing by standard procedures lead to heavy gears. The weight of gears can be reduced using Topography Optimization (TO) [1], which takes a 3-dimensional design and cuts away mass within it to achieve the most efficient design. Structure optimized through Topography Optimization can result in any shape within its design region. TO is an effective tool in performance and design, especially applying it in aeronautical engineering. Engineers employ TO at the level of design concept, due to the forms that naturally occur, the result is hard to manufacture [3]. When the optimized workpiece is needed to be manufactured through the conventional method such as drilling, casting, or milling, the constraints need to be applied in order to avoid flaws and cavities to the workpiece. It is an important key part of a design for manufacturing. This work explores the use of this numerical method to obtain a durable design of a gearbox while keeping the mechanical performance similar to the original design. The objective of this work is to apply TO in order to minimize the mass of an aircraft engine gearbox design for a better and more weight efficient design. Improvement in design of an aircraft gearbox creates a more flexible option
for engineers to design a better gearbox, as well as minimize using irrelevant materials, and reducing over designing of the gears [1]. In Section 2 a brief overview of the topology optimization is given, followed by the research methodology and the numerical results in Sections 3 and 4 respectively where static analysis between original and optimized gears are compared, and finally conclusions.

2. Overview of Topology Optimization

TO is a mathematical method which optimizes material layout, that is for the given boundary conditions, it modifies the original geometry with the objective of minimizing the weight and maximizing the mechanical performance capabilities of the entire system of components [3]. TO is different from shape optimization and sizing optimization, since it can design and obtain any shape within the design, instead of dealing with a pre-set configuration [3]. In Topology Optimization, the loads and constraints are defined first, the volume of the mechanical component will also be defined, and then from the simulation, the software will generate a part shape that will satisfy the loads and constraints while minimizing the mass of the mechanical component and maximize its stiffness. TO also undergo a large amount of development since its introduction in the seminal paper written by Bendsoe and Kikuchi in 1988 [4] currently these parameters are under development, density, level set, topological derivative, phase field, evolutionary and several others parameters [4]. A topology optimization problem can be written in the general form of an optimization problem as [3]:

\[
\text{Minimize } F = F(u(\rho), \rho) = \int_{\Omega} f(u(\rho); \rho) d\nu \\
\text{Subject to: } G_0(\rho) = \int_{\Omega} \rho dV - V_0 \leq 0 \\
G_j(u(\rho), \rho) \leq 0 \text{ with } j = 1, \ldots
\]

The objective function \( F(u(\rho), \rho) \) represents the quantity that is being minimized for the best possible performance [3]. The material distribution as the problem variable is described by the density of the material used at each location \( \rho(u) \) [3]. If the material is present, then it is indicated by 1, if the material is absent, it is then indicated by 0. The design space (\( \Omega \)), this equation indicates the allowable volume within the design [3]. \( m \) constraints \( G_j(u(\rho), \rho) \leq 0 \) a characteristic of a solution that must be satisfied [3]. For example, the maximum amount of the material that needs to be distributed (volume constraint) or the maximum stress values [3].

3. Research Methodology

This work is carried out by means of the engineering software ANSYS [5] to apply Topology Optimization to the gearbox, and SOLIDWORKS [6] to assemble the gearbox. Firstly, an acceptable design of an aircraft engine gearbox has to be obtained, therefore, the boundary conditions are applied at each gear. Which is statically analysed by means of ANSYS Static Structural module [5] to obtain the distribution of von Mises stress for each gear of the gearbox. Secondly, each gear is optimized, in terms of mass, with the Topology Optimization module of ANSYS [1] [7]. After that, we proceed by redefining the geometry of the gear according to the optimized mesh obtained. Finally, the new geometry is statically analysed in order to check if the maximum von Mises stress has been kept approximately unchanged.

3.1. Gearbox model

The aircraft gearbox chosen for this work is a design concept of a coaxial helicopter transmission engine retrieved from the Reference [8]. It does not actually exist, however, the operative condition such as engine power, material, or other engine specifications must be approximate from a similar sample e.g., Arrius 2R [9] coaxial helicopter gearbox. The goal is to reduce the mass of the gearbox while maintaining acceptable the mechanical performance. The material chosen for the gears is Titanium Alloy for its high yield strength. Figure 1 below shoes the original design of the gearbox.
From referenced engine specification and know condition of the gears, the following resultant forces are found acting on the tooth of each gear:

\[ F_1 = \frac{T_1}{r_1} = \frac{77.789}{34.227 \times 10^{-3}} = 2272.738 \, N \]  
\[ F_2 = \frac{T_2}{r_2} = \frac{94.868 \times 10^{-3}}{233.394} = 2460.197 \, N \]  
\[ F_3 = \frac{T_3}{r_3} = \frac{34.225 \times 10^{-4}}{6682.720} = 6682.720 \, N \]  
\[ F_4 = \frac{T_4}{r_4} = \frac{1073.612}{149.856 \times 10^{-3}} = 7164.291 \, N \]

3.2. Mesh detail

The generated fine mesh uses Patch Independent with tetrahedrons method and refined for proximity and curvature. The sizes of each element various according to the size of the gear itself. The values of element size and element number of each respective gear are shown in Table 1. Figure 2 shows an example of mesh generated in one gear.

| Gears          | Element Size (mm) | Element Number (Million) |
|----------------|-------------------|---------------------------|
| Large Helical  | 3                 | 1.595                     |
| Large Bevel    | 1.0-0.1           | 4.756                     |
| Small Helical  | 1.0-0.1           | 2.097                     |
| Small Bevel    | 1.0-0.5           | 1.189                     |

3.3. Boundary condition

Each gear has similar boundary conditions applied such as resultant force and fixed support. The resultant force is applied at the surface of a single tooth, while the fixed support is applied along the inner shaft surface of the gear. Figure 3 below shows two boundary conditions applied to a gear.
3.4. Topology Optimization solver module
The selected design region of each gear is the front and back surfaces of a slice of gear which includes one single tooth, as shown in Figure 4. While the outer and inner shaft surfaces, and all teeth are excluded from the design region. By doing so, we take into account of the axial symmetry of the gear during the optimization process.

4. Numerical results
In the following, we report the numerical results for the four gears. The mesh sensitivity study is carried out in order to verify the influence of the mesh on some of the parameters involved in the analysis. Redefining the geometry by matching exactly the optimized mesh can be quite troublesome, therefore, the reduction of mass obtained after the application of the TO does not necessarily match the reduction obtained after redefining the geometry. Figure 5 shows von Mises stress distribution at each gear, while Figure 6 shows the results obtained with the TO module of each respective gear together with the geometry redefined.
4.1. Large helical gear

Values of FEM and TO results of Large Helical Gear are reported in Table 2; it can be seen that there is a 41.27% increase in maximum von Mises stress and a 15.80% decrease in mass as final result of the optimization process. The result for this gear can be considered acceptable considering the high yield strength of the adopted material. Figure 7 shows the original and the final geometry of the gear.

| Parameters                  | Fine     | Medium | Coarse |
|-----------------------------|----------|--------|--------|
| Original maximum von Mises Stress (MPa) | 102.70   | 106.95 | 98.66  |
| Final maximum von Mises Stress (MPa)   | 145.08   | -      | -      |
| % Increase in Stress          | 41.27%   | -      | -      |
| Total Deformation (mm)        | 0.0679   | 0.0678 | 0.0602 |
| Final Deformation (mm)        | 0.1372   | -      | -      |
| % Increase in Total Deformation | 202     | -      | -      |
| % Of Mass Removed             | 38.29    | 47.37  | 37.53  |
| Original Mass (kg)            | 13.9     | -      | -      |
| Final Design Mass (kg)        | 11.704   | -      | -      |
| % Mass of Original            | 84.20    | -      | -      |
Figure 7. Large helical gear (a) original design, (b) final design.

4.2. Large bevel gear
Values of FEM and TO results of Large Bevel Gear are reported in Table 3; notice that there is a 45.2% decrease in the maximum von Mises stress and a 31.15% decrease in mass. The reason for this drastic decrease in stress could be a flaw in the original design, and by removing the mass and adding fillet near centre of the gear the von Mises stress decrease tremendously. Therefore, the result for this gear is greatly acceptable. Figure 8 shows the geometry of the gear before and after optimization.

Table 3. Data of large bevel gear.

| Parameters                  | Fine     | Medium | Coarse   |
|-----------------------------|----------|--------|----------|
| Original Stress (MPa)       | 726.53   | 593.42 | 1127.30  |
| Final Stress (MPa)          | 397.81   | -      | -        |
| % Increase in Stress        | -45.25   | -      | -        |
| Total Deformation (mm)      | 0.3060   | 0.3059 | 0.3117   |
| Final Deformation (mm)      | 1.4179   | -      | -        |
| % Increase in Total Deformation | 463  | -      | -        |
| % Of Mass Removed           | 36.39    | 35.99  | 35.80    |
| Original Mass (kg)          | 1.04     | -      | -        |
| Final Design Mass (kg)      | 0.716    | -      | -        |
| % Mass of Original          | 68.85    | -      | -        |

Figure 8. Large bevel gear (a) original design, (b) final design.

4.3. Small helical gear
Values of FEM and TO results for the Small Helical Gear are reported in Table 4; For this case, there is a 5.88% increase in the maximum von Mises stress and a 16.32% decrease in mass. The result for this gear is acceptable. Figure 9 shows the original and final geometry of the gear.

Figure 9. Small helical gear (a) original design, (b) final design.
4.4. Small bevel gear
Values of FEM and TO results of the Small Bevel Gear are reported in Table 5; there is a 9.77% increase in equivalent stress and a 6.73% decrease in mass. The result for this gear is also acceptable. Figure 10 shows the original and final geometry.

### Table 4. Data of small helical gear.

| Parameters               | Fine     | Medium  | Coarse   |
|--------------------------|----------|---------|----------|
| Original Stress (MPa)    | 298.38   | 296.21  | 303.21   |
| Final Stress (MPa)       | 315.92   | -       | -        |
| % Increase in Stress     | 5.88     | -       | -        |
| Total Deformation (mm)   | 0.0477   | 0.0477  | 0.0476   |
| Final Deformation (mm)   | 0.0658   | -       | -        |
| % Increase in Total Deformation | 138     | -       | -        |
| % Of Mass Removed        | 36.68    | 35.41   | 35.18    |
| Original Mass (kg)       | 0.38     | -       | -        |
| Final Design Mass (kg)   | 0.318    | -       | -        |
| % Mass of Original       | 83.68    | -       | -        |

### Table 5. Data of small bevel gear.

| Parameters               | Fine     | Medium  | Coarse   |
|--------------------------|----------|---------|----------|
| Original Stress (MPa)    | 139.51   | 158.11  | 154.85   |
| Final Stress (MPa)       | 153.14   | -       | -        |
| % Increase in Stress     | 9.77     | -       | -        |
| Total Deformation (mm)   | 0.0122   | 0.0122  | 0.0121   |
| Final Deformation (mm)   | 0.0176   | -       | -        |
| % Increase in Total Deformation | 145     | -       | -        |
| % Of Mass Removed        | 34.43    | 39.64   | 39.14    |
| Original Mass (kg)       | 0.312    | -       | -        |
| Final Design Mass (kg)   | 0.291    | -       | -        |
| % Mass of Original       | 93.27    | -       | -        |

![Figure 10. Small bevel gear (a) original design, (b) final design.](image)

In conclusion, in Figure 11 the comparison between the original and the final maximum von Mises stress is showed for the four gears, Table 6 reports the obtained total reduction of mass while Figure 12 shows the assembly of the gearbox after optimization.
Figure 1. Comparison of the original and final maximum von Mises stress values.

Table 6. Final gearbox mass reduction result.

| Parameters          | Values   |
|---------------------|----------|
| Total Original Mass (kg) | 15.632 kg |
| Total Final Mass (kg)   | 13.029 kg |
| Total % Mass Reduced   | 16.65%    |

Figure 2. Final design of the gearbox.

5. Conclusions
This paper showcases a method of applying Topology Optimization to a pre-existing design of an aircraft engine gearbox and succeeds in reducing the mass and maintaining similar mechanical performance. ANSYS Topology Optimization module is applied to an aircraft engine gearbox in order to minimize the mass by keeping the mechanical performance unchanged. The simulations carried out allow us to obtain a total reduction of 16.65% for the entire system while the maximum von Mises stress estimated on each gear is maintained approximately close to the one estimated before performing the optimization. The experiment results are achievable numerically, with an overall 16.65% in mass reduction and 5% to 40% increase in equivalent stress. Better results can be obtained through redefining the geometry more accurately according to the optimized TO result. However, the results given by the Topology Optimization process are not suited for manufacturing. Therefore, proficiency and techniques in redefining the geometry manually contributes a great deal in the final design result of the geometry. The results from this research show that, it is possible to reduce material used to manufacture the entire set of gear without exceeding the mechanical performance limit of the
material used in this scenario. Since the overall mass of the gearbox has been reduced, this allows for a more flexible design and improvement in gear efficiency of fuel consumption. The study added more possibilities for a better design, lighter weight, similar durability, and more topologically efficient gearbox.

References
[1] P Chandra Rao, M Anil Kumar and M Nirmal Devi Kiran 2019 Topology Optimization of Gear Box Using ANSYS ISSN: 2278-2808
[2] Vaibhav Pimpalte and S C Shilwant 2017 Topology Optimization of Gears from Two Wheeler Gear Set Using Parametric Study E-ISSN: 2278-1684, P-ISSN: 2320-334X
[3] Bendsøe M P and Sigmund O 1999 Material interpolation schemes in topology optimization DOI: https://doi.org/10.1007/s004190050248
[4] N Aage M, G Allaire G, G Allaire R, G Allaire F, G Allaire F, L Ambrosio G, et al. 1970 Topology Optimization Approaches DOI: 10.1007/s00158-013-0978-6
[5] Ansys (n.d.). Topology Weight & Load Optimization Software
[6] SolidWorks. 3D CAD design software (n.d.)
[7] Twin Cities 2019 ANSYS User Meeting Topology Optimization
[8] Shastry Animesh Kumar 2019 Coaxial Helicopter Transmission Grabcad.com
[9] Safran-helicopter-engines 2018 Arrius 2R