TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue I, March, 2025

DESIGN and STRUCTURAL PERFORMANCE COMPARISON of HELICAL PLANET GEARBOXES for GEARED TURBO FAN ENGINE

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Abstract: *GTF (Geared Turbo Fan) engines have systems defined as advanced engine architecture. In this system, a double helical planetary gearbox is used between the fan and the compressor. In this study, finite element analyses were conducted for double helical planetary gearbox with 4 different helix angles and 3 different titanium alloys. It was aimed to determine the optimum helix angle and titanium alloy. It was observed that Ti-6Al-4V alloy with the helix angle 25° had the minimum deformation as 0.033 mm, occurred stress as191.00 MPa and strain as 0.0018 values. It was obtained from the analyses results and comparisons that Ti-6Al-4V alloy with the helix angle 25° was the optimum for applications.*

Key words: *Gear Design, Geared Turbo Fan Engine, Finite Element Analysis, Helical Planet Gearbox, Titanium Alloys*

1. INTRODUCTION

GTF (Geared Turbo Fan) engines are new, advanced engine architecture. They have revolutionized the aviation industry in recent years. Unlike conventional turbofan engines, GTF engines use a gearbox between the low pressure compressor and turbine. Gearbox connects the fan directly to the main engine. This architecture allows the components to operate at their optimum speed. The fan drive gear system can operate with a reduction ratio of 3:1 or higher. A larger diameter fan could run slower, at the same time a low-pressure compressor and low pressure turbine could run relatively faster with the help of this geometry. These allow more efficient-lower fuel consumption, quieter and environmentally friendly operations. The geared turbofan concept itself existed in the 1970s, however technological constraints prevented its success. About 30 years later, in the early 2000s, Pratt & Whitney began developing the GTF engine concept. The demo engine was completed over 400 hours of testing, including 250 hours of ground test and 120 hours of flight test [1]. In 2008, the first GTF engine, the PW1100G-JM, was tested for use on Bombardier C Series aircraft. After this successful entry into the civil aviation market, in 2011 Airbus A320neo family selected GTF engines as standard power source. GTF engines have been also used on Boeing 777X aircraft. Along with P&W, Rolls-Royce developed Ultra Fan concept. Back in today, GTF Engines are used in a wide range of application. From narrow/wide-body commercial engines such as Airbus A320neo, Boeing 777X and 737 MAX for commercial applications to regional or business jets such as Gulfstream G600, Bombardier CRJ Series, and Bombardier Global 7500 for jet applications [1,2].

In many applications in industry for automotive, aerospace, industrial, shipping, textile, wind turbine gear boxes are used extensively. Different kinds of gear boxes such as automatic, manual, differential, planetary gear boxes are in use for various applications. The main aim of a gear box set is transmitting power from one rotating shaft to another [2]. Helical planetary gear sets are used commonly in many automotive applications. On the other hand, double-helical gear sets have high load

Received: 30.01.25; **Similarities**: 05.03.25: **Reviewed**: 19.02./17.02.25: **Accepted**:18.03.25.

carrying capacity and ability to eliminate axial thrust forces. Double-helical gearbox geometry is a specific choice for high speed aerospace and rotorcraft applications [3]. Planetary gear geometry includes 3 main and 1 auxiliary part. These could be listed as a ring gear, a sun gear, several numbers of-at least 3-planet gears and a carrier that hold planet gears as an auxiliary part. Also, these listed parts could be arranged in different ways. As an example, ring gear or sun gear may be chosen as fixed and other gears are rotated about the fixed one's axis. Planet gears are rotated with help of the carrier and about the carrier [3-6]. Planet gearboxes are come with both improvement effects and challenging sides. The geometry itself allows narrow space applications due to its compact structure. Besides that compactness, it provides high power and torque density. Torque density can be increased by adding planet gears. Considering that it works high transmission ratios, planetary geometry offers noise and vibration reduction compared to conventional gearbox geometry. Design of planetary gearboxes have some sort of complexities rather than standard gearbox design. Because of this complexity, productions costs could be potentially increased [4-6].

Understanding the engine architecture and configuration is critical for material selection. Basically, an aircraft jet engine has two main sections according to working temperatures. These could be listed as cold section and hot section. Cold section includes components that work in relatively lower temperatures such as fan, gearbox and if it is a GTF engine, low and high pressure compressors (LPC-HPC). Hot section have components in its structure that work in higher temperatures. For example combustion chamber, high and low pressure turbines (HPT-LPT) and exhaust nozzle [7]. Operating temperature gives the information about which materials could be suitable for related part of the engine. Considering the location of fan drive gear system, titanium alloys are observed as dominant material type [8]. Titanium in general is used to decrease weight by replacing heavy steel alloys in airframes and super alloys in low-temperature components of gas turbines. Titanium is also used to replace aluminum alloys where temperature intervals are off the limit for aluminum or in sections where fatigue and corrosion are repetitive problems [9]. Except titanium, nickel based alloys could be used in high pressure compressor where is closer to hot section. Also, aluminum alloys could be used in the fan section of the engine [7, 10].

From the perspective of the industry, fan drive gear systems or gearbox architectures are regarded as a crucial aspect of Contact Stress Analysis. A detailed study of the contact stresses occurring between mating gears is the most significant task in gear design, since they are a decisive parameter to determine the gear dimensions. When gears are under a load, high stresses are concentrated at the bottom of the teeth. This concentration of high stress increase fatigue failure possibility at the gear teeth [11].

Gear failure is known as a common issue for gears. Some gear failures could be listed as wear, tooth breakage, fatigue and so on. Fatigue is an often encountered failure type in gears or gearbox sets. Also, there are some different categorization options for classifying gear failure modes. One of the typical gear failure is Abrasive wear. This type of failure could happen when there is lubrication issue or particle contamination. Another common wear type is Corrosive wear. Like abrasive wear, corrosive wear is observable as well. It is caused in surface distortions. Another significant failure type that should be mentioned is fatigue pitting. Cyclic load situations are the main cause of this failure. It could be resulted as fatigue cracks both tooth surface of gear or under the surface [12, 13].

Today, many computer-based tools have been available to help design and analysis cycle of the structures. Solid modelling using CAD methods assists the designers to define the parts and assembly of the system and to utilize the geometry in applications such as simulation, analysis and prototyping. Virtual prototype simulations, static, kinematic and dynamic analysis can be conducted with CAE methods [14-16].

In this study, double-helical gearboxes consisting of five planets in a 3:1 ratio was designed with reference to the gearbox geometry, found in GTF engines with Autodesk Fusion software. The geometry included 4 parts. These were ring gear, sun gear, planetary gears and carrier respectively. Helix angle was chosen as a variable. Based on this information, gearbox was designed for 4 different helix angles as 25°, 26.5°, 28.5° and 30°.

Using ANSYS Static Structural module; the contact stresses that may occur in the gears with the relevant rpm values were analyzed for 4 different geometries. Besides geometry variations, 3 different type of titanium alloy were used as material variable as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo and Ti-13V-11Cr-3Al in analyses.

2. MATERIAL AND METHOD

2.1 Numerical Calculations and Design

With planetary systems, large reduction ratios are achievable in compact arrangements. In this study, considering the working environment of the gearbox and the parts, the ring gear is chosen as fixed. Determination of teeth numbers of gears are directly related to reduction ratio, fixed gear and constraint equations for mount ability.

$$i_0 = \frac{z_r}{z_s} \quad (1)$$

$$n_c(1 + i_0) = n_s + i_0 \times n_r \quad (2)$$

$$i_S/_C = 1 + \frac{n_R}{n_S} \quad (3)$$

$$z_r = z_S + 2\, z_P \quad (4)$$

$$\frac{z_S+|z_R|}{P} = \text{Integer number} \quad (5)$$

Equation (1) represents gear ratio, equation (2) and (3) represents reduction ratio according to equation (1). Equation (4) and (5) are mount ability equations for feasible application of geometry [17].

Design parameters of the gears were determined using related equations and references [18]. Those parameters are given in Table 1.

Table 1. Parameters of designed gearboxes

Name of the parameter	Value
Module	2.5
Number of teeth of ring gear	120
Number of teeth of sun gear	60
Number of teeth of planet gear	30
Reduction ratio	3:1
Helix angles	25°- 26.5° 28.5°- 30°
Pressure angle	20°

Part list and exploded view and engineering drawing of the designed gearboxes are shown in Figure 1 and 2, respectively.

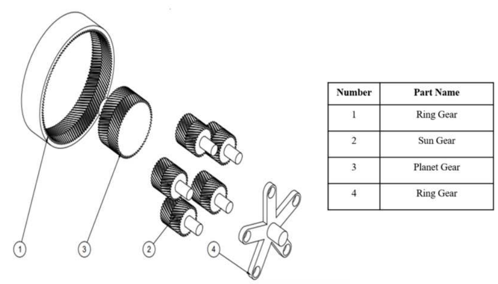


Fig. 1. Part list and exploded view of double helical planetary gearbox geometries

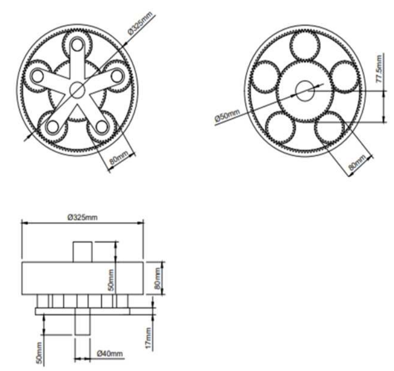


Fig. 2. Engineering drawings of double helical planetary gearbox geometries

Gearbox geometries were divided into 3 sub geometry for contact stress analysis (Table 2). The first one was planet-sun geometry (Figure 3). In setup steps, the sun gear was adjusted as fixed and planet gear had rotational velocity. For sun-planet geometry, planet gear was settled as fixed and rotational velocity was applied for sun gear. Lastly, for ring-planet geometry (Figure 4), ring gear the internal tooth part was selected as fixed and rotational velocity was applied for planet gear.

Table 2. Sub geometry setup of gearbox

Name of Sub geometry	Applied setup
Ring-planet	Ring gear is fixed, planet gear has rotational velocity

Planet-sun	Internal rim of sun gear is fixed, planet gear has rotational velocity
Sun-planet	Internal rim of planet gear is fixed, sun gear has rotational velocity

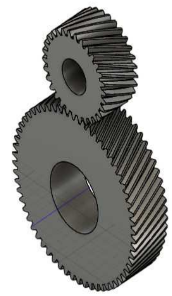


Fig. 3. Planet-sun sub geometry

Fig. 4. Ring-planet sub geometry

After the design phase of the geometries with the proper parameters and calculations, the analysis setups were created in the ANSYS Static Structural module to calculate the occurred stresses, strains, deformations and factor of safety values. For the analyses, the rotational velocity magnitude was applied by dividing into the 5 second periods in rad/s unit to the gears. The contact stress values were obtained from those analysis sets.

2.2 Titanium Alloys

In this study, 3 different type of titanium alloy were assigned for designed geometries.
Titanium alloys can be categorized as 3 main categories. Those are; alpha alloys, alpha beta alloys and beta alloys.
Alpha type titanium alloys or pure titanium are not suitable for heat treatment processes, on the other hand weldability of this material group is on the higher side. Also, they have better corrosion resistance than Beta alloys.Ti-8Al-1Mo-1V is a near-alpha alloy, Ti-7Al-12Zr and Ti-5Al-5Sn-5Zr are called as super alphas and Ti–6Al-2Sn-4Zr-2Mo are the examples of alpha alloys. Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) is developed to operate at high temperatures. It exhibits better mechanical performance than Ti-6Al-4V. In this study, Ti-6Al-2Sn-4Zr-2Mo is selected as material variable for designed geometries.
Alpha-beta type titanium alloys are suitable for heat treatments on the contrary of alpha alloys and have the highest weldability. Strength range of this material group is in between medium to high. Due to the desired combination of ductility, toughness, and strength; alpha-beta alloys are the most commonly used. Ti-6Al-4V is selected as material variable for designed geometries. Besides alloy of Ti-6Al-4V; Ti-5Al-2Sn-2Zr-4Mo-4Cr, Ti-3Al 2.5V and Ti-6Al-2Sn-4Zr-6Mo can be listed as some other significant alpha-beta alloys.
Beta alloys of titanium are considered as totally heat treatable, have relatively higher tensile-fatigue strength and generally suitable for welding. Beta alloys are denser when compared with other types of alloys. Ti-13V-11Cr-3Al (B 120 VCA), Ti-35V-15Cr (Alloy C) and Ti-4.5Fe-6.8Mo-1.5Al (TIMETAL LCB) are the examples of beta alloys. [19-25]. In this study, Ti-13V-11Cr-3Al is used in contact stress analysis as material variable. Mechanical properties of each alloy assigned as material in the analyses are given in Table 3, 4 and 5, respectively [26].

Table 3. **Mechanical properties of Ti-6Al-4V**

Name of the property	Value
Density	4,425 kg/m3
Young's Modulus	114,000 MPa
Poisson's Ratio	0.36
Tensile Yield Strength	1,182 MPa
Tensile Ultimate Strength	1,050 MPa

Table 4. **Mechanical properties of Ti-6Al-2Sn-4Zr-2Mo**

Name of the property	Value

Density	4,540 kg/m3
Young's Modulus	114,000 MPa
Poisson's Ratio	0.36
Tensile Yield Strength	890.5 MPa
Tensile Ultimate Strength	974.5 MPa

Table 5. Mechanical properties of Ti-13V-11Cr-3Al

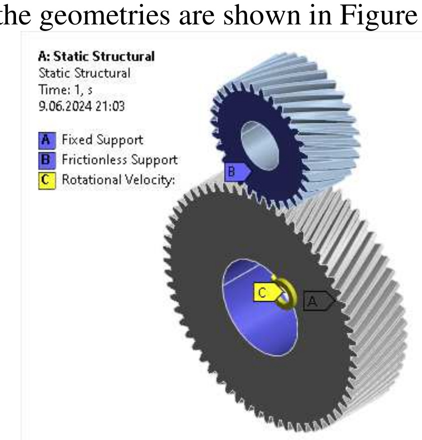
Name of the property	Value
Density	4,820 kg/m3
Young's Modulus	101,400 MPa
Poisson's Ratio	0.3
Tensile Yield Strength	869.4 MPa
Tensile Ultimate Strength	906 MPa

2.3 Helix Angles

4 different helix angles as 25°, 26.5°, 28.5° and 30° were applied to the gear geometries Pressure angle for each set was selected as 20°.

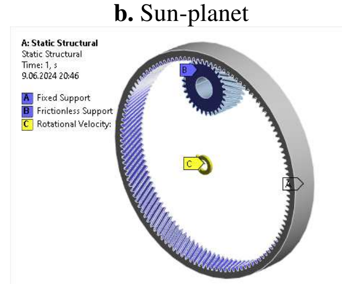
2.4 Analysis Settings

For the analyses, loads were defined in Ansys Workbench Environment. 1,021 and 340 rad/s rotational velocity magnitudes were applied to planet and sun gears with the ratio.
Internal rims of shaft connections and front faces of the rotated gears were assigned as fixed and frictionless supports. Also, front faces of rotating gears were selected as frictionless supports. Applied analyses settings of the geometries are shown in Figure 5.



a. Planet-sun

b. Sun-planet



c. Ring-planet

Fig. 5. Analyses settings of sub-geometries

2.5 Mesh Settings

For the accuracy and consistency of the analyses results, the mesh element quality and skewness parameters were considered as critical parameters. For high quality model analyses; maximum skewness value should be under the 0.9, and average value should be 0.4.Minimum element quality value should be higher than 0.1 [24]. In this study, in sizing section element size kept default, adaptive sizing was on, transition type was selected as slow and span angle center was settled as medium to create accurate and consistent analyses results. Additionally, patch independent method one of the tetrahedron methods was applied with minimum size limit of 3 mm. The maximum skewness and minimum element quality values were obtained as 0.74 and 0.35, respectively. Those obtained values were acceptable to provide accurate and efficient analyses results.

3. RESULTS AND DISCUSSION

3.1 Deformations

The deformation values were listed in Table 6. The maximum values were observed on the planet sun sub geometries for all helix angles with the material of Ti-13V-11Cr-3Al alloy as 0.091 mm. The minimum values were obtained for the sun-planet sub geometry with the material of Ti-6Al-4V and 25° helix angle as 0.033 mm.

Table 6. Deformations in unit of mm

	Name of the Alloy			
Helix angle	**Ti-6Al-2Sn-4Zr-2Mo**	**Ti-6Al-4V**	**Ti-13V-11Cr-3Al**	**Sub geometry**
25°	0.075	0.074	0.091	Planet-sun
25°	0.035	0.033	0.042	Sun-planet
25°	0.049	0.049	0.06	Ring-planet
26.5°	0.075	0.074	0.091	Planet-sun
26.5°	0.037	0.036	0.047	Sun-planet
26.5°	0.055	0.064	0.079	Ring-planet
28.5°	0.074	0.073	0.090	Planet-sun
28.5°	0.039	0.038	0.046	Sun-planet
28.5°	0.055	0.055	0.067	Ring-planet
30°	0.074	0.073	0.090	Planet-sun
30°	0.043	0.042	0.051	Sun-planet
30°	0.088	0.087	0.108	Ring-planet

3.2 Stresses

The stress values were given in Table 7. Maximum stress was occurred as 563.67 MPa on the planet-sun sub geometry with the helix angle of 25° and Ti-13V-11Cr-3Al alloy material. Minimum value was observed as 191 MPa at the sun-planet sub-geometry with the helix angle of 25° and Ti-6Al-4V alloy material.

Table 7. Stresses in unit of MPa

	Name of the Alloy			
Helix angle	**Ti-6Al-2Sn-4Zr-2Mo**	**Ti-6Al-4V**	**Ti-13V-11Cr-3Al**	**Sub geometry**
25°	500.68	497.60	563.67	Planet-sun
25°	200.32	191.00	216.82	Sun-planet
25°	479.24	491.16	495.82	Ring-planet
26.5°	626.41	618.19	681.30	Planet-sun
26.5°	255.72	251.48	260.54	Sun-planet
26.5°	672.17	683.29	784.17	Ring-planet
28.5°	647.33	641.98	729.23	Planet-sun
28.5°	317.59	291.80	344.98	Sun-planet
28.5°	614.97	645.36	717.60	Ring-planet
30°	485.87	477.14	519.46	Planet-sun
30°	240.06	240.83	260.00	Sun-planet
30°	783.18	766.89	836.19	Ring-planet

3.3 Strains

The strain values were given in Table 8. Maximum strain was observed as 0.0061 on the planet-sun sub geometry with the helix angle of 25°and Ti-13V-11Cr-3Al alloy material. Minimum value was observed as 0.0018 at the sun-planet sub-geometry with the helix angle of 25° and Ti-6Al-4V alloy material.

Table 8. Strains

	Name of the Alloy			
Helix angle	**Ti-6Al-2Sn-4Zr-2Mo**	**Ti-6Al-4V**	**Ti-13V-11Cr-3Al**	**Sub geometry**
25°	0.0049	0.0048	0.0061	Planet-sun
25°	0.0019	0.0018	0.0024	Sun-planet
25°	0.0042	0.0041	0.0050	Ring-planet
26.5°	0.0061	0.0062	0.0078	Planet-sun
26.5°	0.0023	0.0022	0.0027	Sun-planet
26.5°	0.0062	0.0064	0.0083	Ring-planet
28.5°	0.0059	0.0059	0.0076	Planet-sun
28.5°	0.0029	0.0027	0.0036	Sun-planet
28.5°	0.0058	0.0061	0.0076	Ring-planet
30°	0.0045	0.0044	0.0054	Planet-sun
30°	0.0022	0.0022	0.0027	Sun-planet
30°	0.0069	0.0067	0.0083	Ring-planet

3.4 Factor of Safety Values

FOS (Factor of safety) values were observed and considered as another important parameter for the comparison. Maximum FOS was found as 5.5 for the sun-planet sub-geometry with the helix angle of 25° and Ti-6Al-4V alloy material. The minimum FOS was observed as 1.5 for the planet-sun sub geometry with the helix angle of 25° and Ti-13V-11Cr-3Al alloy material.

From all those analyses it was observed that Ti-6Al-4V alloy with the helix angle 25° had the minimum deformation as 0.033 mm, occurred stress as 191.00 MPa and strain 0.0018 values. Also it can perform with the maximum factor of safety value as 5.5. It was obtained from the analyses results and comparisons that Ti-6Al-4V alloy with the helix angle 25° was the optimum for the helical planet gearboxes for the geared turbo fan engines.

4. CONCLUSION

In this study, double-helical gearboxes consisting of five planets in a 3:1 ratio was designed with reference to the gearbox geometry found in GTF engines. Helix angle was chosen as a variable. Based on this information, gearbox was designed for 4 different helix angles as 25°, 26.5°, 28.5° and 30°. Using ANSYS Static Structural module; the contact stresses that may occur in the gears with the relevant rpm values were analyzed for 4 different geometries. Besides geometry variations, 3 different type of titanium alloy were used as material variable as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo and Ti-13V-11Cr-3Al in analyses. All the deformation, occurred stress, strain and FOS values were presented for geometry variables with different helix angles and materials. From all those analyses it was observed that Ti-6Al-4V alloy with the helix angle 25° had the minimum deformation as 0.033 mm, occurred stress as191.00 MPa and strain as 0.0018 values. Also it can perform with the maximum factor of safety value as 5.5. It can be concluded from the analyses results and comparisons that Ti-6Al-4V alloy with the helix angle 25° was the optimum for the helical planet gearboxes for the geared turbo fan engines.

5. NOMENCLATURE

$i_0 = Gear\ ratio$
$z_r = Number\ of\ teeth\ of\ the\ ring\ gear$
$z_s = \ Number\ of\ teeth\ of\ the\ sun$ gear
$z_P = Number\ of\ the\ teeth\ of\ the\ planet\ gear$
$n_c = Number\ of\ rotation\ of\ the\ carrier$
$n_s = Number\ of\ rotation\ of\ the\ sun\ gear$
n_r
$= Number\ of\ rotation\ of\ the\ ring\ gear$
$i_S/_c = Gear\ ratio\ of\ the\ sun\ gear\ and\ carrier$
$p = Number\ of\ planet\ gears$

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PROIECTARE și PERFORMANȚĂ STRUCTURALĂ, COMPARAȚIE CUTII DE VITEZE PLANETARE ELICOIDALE pentru MOTOR TURBOVENTILATOR CU ANGRENAJE

Rezumat: *Motoarele GTF (Geared Turbo Fan) au sisteme definite ca arhitectură avansată a motorului. În acest sistem, se utilizează o cutie de viteze planetară dublă elicoidală între ventilator și compresor. În acest studiu, au fost efectuate analize cu elemente finite pentru cutia de viteze planetară dublă elicoidală cu 4 unghiuri diferite de elice și 3 aliaje diferite de titan. Scopul a fost de a determina unghiul optim al helixului și aliajul de titan. S-a observat că aliajul Ti-6Al-4V cu unghiul helix de 25° a avut deformarea minimă de 0,033 mm, tensiunea apărută ca 191,00 MPa și deformarea ca valori de 0,0018. S-a obținut din rezultatele analizelor și comparațiilor că aliajul Ti-6Al-4V cu unghiul helix de 25° a fost optim pentru aplicații.*
Cuvinte cheie: *Proiectarea angrenajului, Motor turboventilator cu angrenaje, Analiza elementelor finite, Cutie de viteze elicoidală, Aliaje de titan*

Abstrakto: GTF (Geared Turbo Fan) motorura si len sistemura definime sar avansime motoroski arxitektura. Ano akava sistemo, jekh dujto helikalno planetarno gearbox si kerdo mashkar o ventilatori thaj o kompresori. Anθ-i kadaja studia, sas kerde analìze e finite elementurenqe vaś o dujto helikàlo planetarno śuruvipen e 4 diferentne helikàlo anglença thaj 3 diferentne titanosqe legure. O ciljo sas te arakhel pes o optimalno angluno helico thaj o titaniumosko lego. Dikhlino sas kaj o Ti-6Al-4V lego e helixesko angluno 25° sas les e minimalno deformacia sar 0.033 mm, kerdas pes streso sar 191.00 MPa thaj deformacia sar 0.0018 valutura. Katar e analizake rezultatura thaj komparacie sas arakhlo kaj o Ti-6Al-4V lego e helixesko angluno 25° sas o optimalno vash e aplikacie.

Ključne vorbe: Dizajno e śerutnengo, Motoro e Turbo Ventilatoresqo e śerutnengo, Analìza e Finite Elementurenqi, Helikàlo Planetosqo Gearbox, Titanium Alloys

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