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title: Advanced Face Gear Technology for Rotorcraft Drive Trains

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ABSTRACT

The angular gear transmission (incident axes at almost 90°) may be obtained by a spur pinion meshing with a face gear. The face gear is obtained as the envelope of standard involute spur gear rotating against flat (or silghtly conical) surface. This configuration allows higher gear ratio, lower noise and is relatively insensitive to gear relative positions with respect to bevel gears. The application of this technology to the helicopter Drive Train offers advantages in terms of reduced number of stages, i.e. fewer and faster components. If this technology is associated with architectures based on the split of the torque, further advantages in terms of volumetric envelope are obtained. Mass savings of about 30% are achievable for the Drive Train Main Gearbox with respect to more conventional architectures based on advanced design.
In the framework of an internal technology readiness program, 11" diameter, Pyrowear 53 material, case hardened face gears have been designed, manufactured (including grinding) and dimensionally inspected. Finally the components have been successfully tested in a split torque arrangement up to 371 kWatt.

1. INTRODUCTION

Face Gears have historically been used for applications with low torque and low to moderate speeds such as turn table drives, textile machinery, etc. These gears for the most part are generated by hobbing or by the pinion shaping method. If increased accuracy was required, the teeth were lapped or shaved. This process allowed the use of Face Gears for precision indexing but offered no substantial improvement for load capacity.

The 90's have seen the exploration of designs using Face Gears for aerospace applications, such as helicopter transmission gearboxes. Face Gears would be used to turn the corner between the horizontal gas turbine engine and the vertical output rotor shaft. This function is currently performed by spiral bevel gears. The problem related to the spiral bevel gears is that a maximum gear ratio up to 3 is feasible, therefore leading to reduction gearboxes with several stages.
The Face Gear approach offers significant advantages in terms of higher gear ratios, lower

number of stages and faster rotating components, leading to lower torque and loads.

The continuous effort to improve the rotorcraft performance and to reduce life cycle costs therefore matches with the opportunities offered by the face gear technology, mainly in terms of lower number of reduction stages, that leads to fewer parts than conventional solutions. This significant parts count reduction translates into lower mass and higher reliability. Dramatic improvements in reliability and maintainability provide a genuine reduction in life cycle costs.

For the above reasons, FiatAvio have undertaken an internal technology readiness program on Face Gears since 1993. The approach has consisted in architectural feasibility studies and technology demonstration by design, manufacturing and testing of aerospace quality standard face gears. The most significat results of the above activities are discussed in the present paper.

2. ARCHITECTURAL FEASIBILITY STUDIES

The World Market Trend on rotorcraft requires life cycle cost reductions and performance enhancements in terms of power density and reliability. As a consequence, innovative approaches in the rotorcraft engine integration shall be pursued to simplify the overall Drive Train. These needs match with the opportunities offered by architectures based on face gears, in particular because of:

- high gear ratios;
- low number of stages;
- faster and lighter rotating components (lower torque).

The aim of the performed architectural feasibility studies has been the investigation of the abovedefined opportunities, particularly in terms of performance (weight, envelope, parts count) and costs.

Two approaches have been taken into account for the Face Gear Drive Train architectures from the Engine to the Main Rotor: a Three Stage Approach and a Two Stage Approach, as shown in **Table 1**.

For sake of comparison, also other approaches have been considered, i.e.:

- advanced architecture based on the split of torque, with two stages and four stages;
- conventional design (**Table 1** reports a conventional approach based on advanced design for a relatively high gear ratio Drive Train).

Table 1: *Architectural Feasibility Studies - Considered Approaches*

	FACE GEAR ARCHITECTURE		ADVANCED SPLIT TORQUE ARCHITECTURE		CONVENTIONAL ARCHITECTURE
	2 STAGES	3 STAGES	2 STAGES	4 STAGES	4 STAGES
NOSE GBX	n.a.	bevel	n.a.	bevel	bevel
MAIN GBX	face	face	bevel	bevel	bevel
	bi-helical	planetary	bi-helical	spur	helical
	n.a.	n.a.	n.a.	bi-helical	planetary

Face Gear Architecture - Three Stage Approach (**Figure 1**)

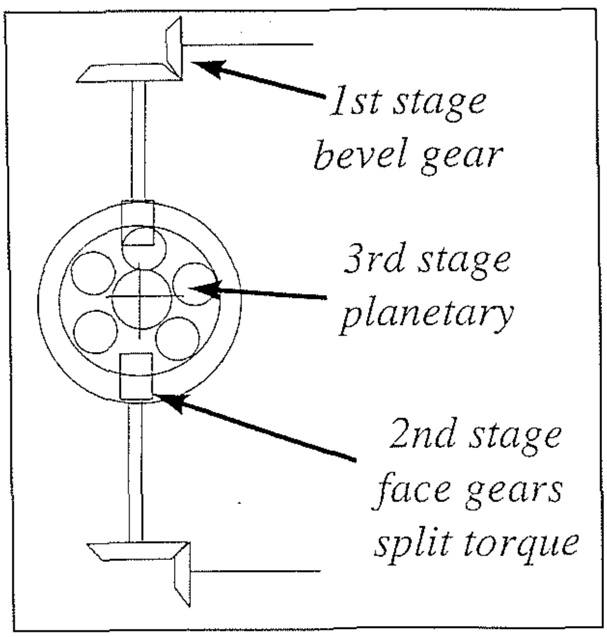
The first reduction stage is based on spiral bevel gears (Nose Gearbox), in order to reduce engine speed and turn the motion torward the main rotor axis.

The key feature of this architecture is the large speed reduction performed in the Face Gears of the 2nd Stage, which allows to design the main gearbox with two reduction stages only.
The input torque to the face gear stage is split between two face gear meshes, either by counter rotating face gears (as shown in **Figure 4**) or with a single face gear with teeth on both sides and properly arranged input pinions.
The latter configuration avoids large face gear deflection and reverse bending on teeth.

The Main Gearbox output stage is a Spur Planetary system.

An overall Drive Train gear ratio around 70:1 is achievable with the Three Stages Approach.

Figure 1: *Face Gear Architecture Three Stage Approach Counter-Rotating Face Gears*



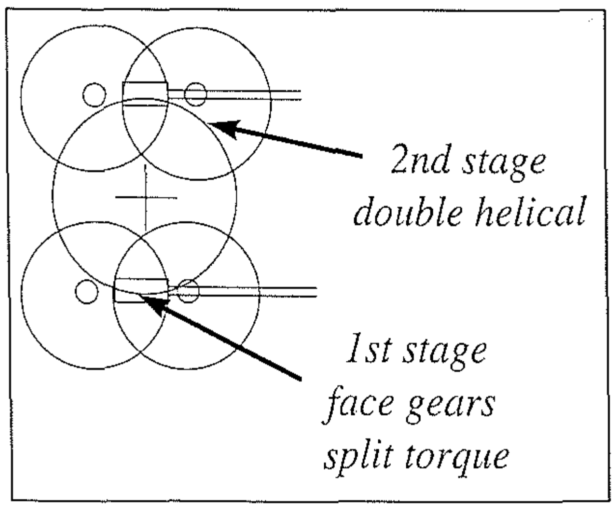
Face Gear Architecture - Two Stage Approach (**Figure 2**)

Input torque from the engine goes directly to the input spur pinion, that meshes with two face gears to split the torque. Each face gear is connected to a Bi-Helical spur pinion, that meshes with a collector gear for torque recombination. In a twin engine architecture, torque is recombined in the collector gear from four torque paths, each consisting of a face gear and a Bi-Helical pinion.

The feasibility of this approach depends on:
- relative positioning of the engines and main rotor;
- relatively high speed clutch in the input pinion;
- envelope in the A/C bay vs. required overall gear ratio.

The affordable overall Drive Train gear ratio of the Two Stages Approach is 50:1 around.

Figure 2: *Face Gear Architecture Two Stage Approach*

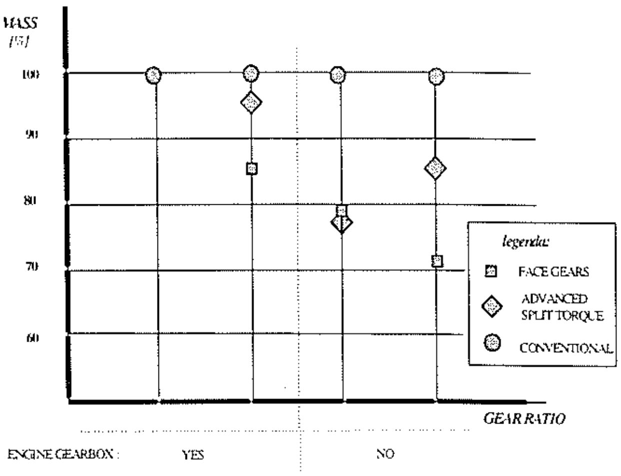


Architectural Feasibility Studies Outcomes

The summary of the performed trade off analyses is reported in **Figure 3** in terms of mass savings versus the gear ratio from the engine interface to the Main Rotor.

For low gear ratios, part of the speed reduction is performed in the engine gearbox; therefore its mass has not been taken into account, as it is part of the engine.

Figure 3: *Relative Mass Figures of Optimized Configurations*



For relatively low Drive Train gear ratios, the Face Gear architectures do not offer significant advantages since part of the speed reduction is achieved within the engine and the rest of speed reduction is well feasible by conventional approaches with comparable mass figures (bevel and planetary gears).

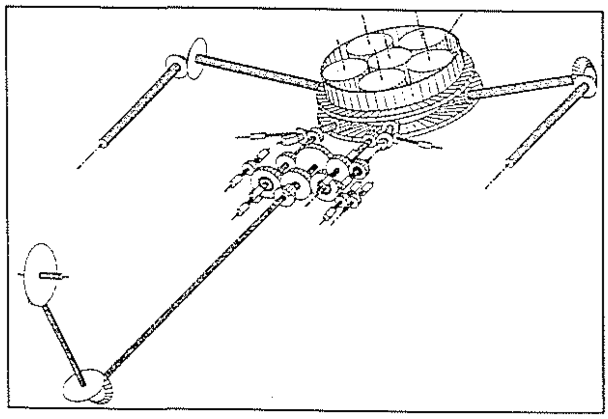
As the gear ratio increases, Face Gear architectures become advantageous in terms of mass, even for architectures with the engine gearbox.
In this case the Two Stage approach is feasible.

The mass of the advanced Bi-Helical split torque architecture is similar to the Face Gear architecture for twin engine configurations without Nose Gearbox and in the lower power range, since the two architectures require the same number of stages.

For higher gear ratios and power range, the Face Gear architecture offers the most significant mass advantage, even compared with advanced split torque architectures. In this case the Three Stage Approach is needed.

In **Figure 4** a possible Drive Train arrangement based on a Face Gear Three Stage Design approach for a high power twin engine helicopter is reported.

Figure 4: *Drive Train arrangement using Face Gears*



The following **Table 2** presents for this application some key Performance Categories of the Main Gearbox, that have been referred to the corresponding figures of the Conventional Approach based on advanced design.

Table 2: *Comparison of Face Gear & Conventional design approach*

Performance Categories	Face Gear Split Torque/ Conventional Approach based on Advanced Design
Mass	72%
Outer Diameter	93%
Height	88%
Vol. envelope	75%
No. of bearings (1)	88%
No. of gear meshes (1)	93%

(1) *No. of parts in the Main Rotor torque path*

Significant reductions have been evaluated in terms of mass (28%), volumetric envelope (25%) and parts count, with consequent advantages in terms of:

- manufacturing recurring cost;
- reliability;
- cost of ownership and support ;

while keeping compatibility with existing envelopes.

3. TECHNOLOGY READINESS PROGRAM

FiatAvio started in 1993 an internal Technolgy Readiness Program on Face Gears aimed at:

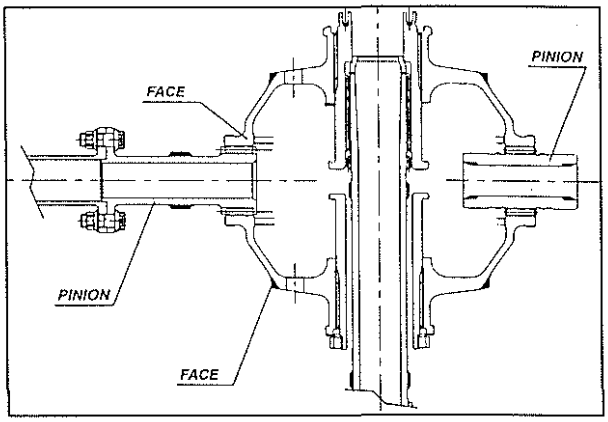
- design;
- manufacturing and inspections;
- rig test in loaded condition to assess functionality and durability.

Design

The reduction stage (**Figure 5**) has been designed to split the input torque, i.e.:

- a spur pinion for input torque;
- a face gear for torque split;
- an idler to recombine torque;
- a face gear for torque output.

Figure 5: *Tested Reduction Stage Architecture*



The selected key design parameters of the reduction stage are:

- gear ratio 4.45:1
- angle between shafts 90°
- power rating 265 Kwatt
- input speed 6000 rpm

The face gears have been designed with an outer diameter of 280 mm. The face width has been designed accounting for:

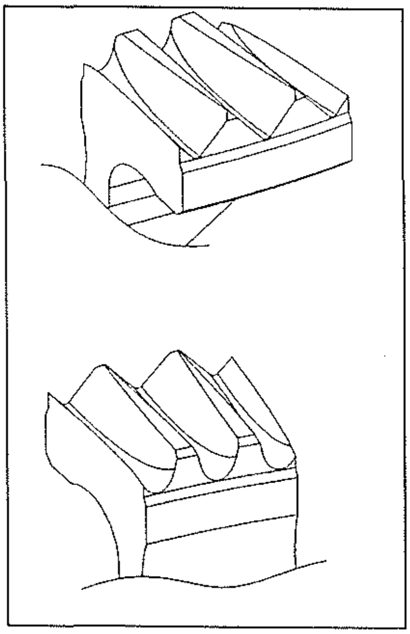
- undercutting of the tooth flank at the inner diameter of the face gear;
- pointing of the top land at the outer diameter of the face gear.

The mesh geometry of the face gear has been defined on the basis on the following design tools:

- face gear tooth geometry definition by a dedicated computer code and by 3D CAD surface modelling
- FEM analysis;
- bending, pitting and scuffing analysis have been performed by a 'quasi-spur gear approach' according with ANSI-AGMA 2001-B88.

The resulting geometry of the tooth is shown in **Figure 6**.

Figure 6: *Face Gear tooth geometry*



The selected material for the face gears and for the spur pinions is Pyrowear 53 per AMS 6308, case carburized.

Manufacturing and Inspections

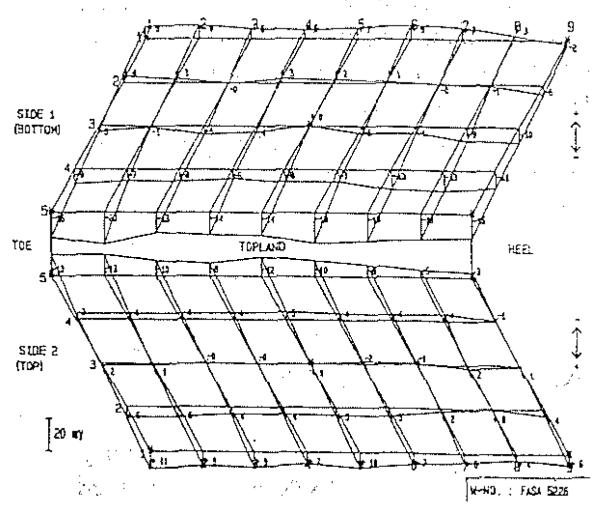
The most challenging issue in the face gear manufacturing is the grinding operation. To this purpose a 5 axes numerically controlled grinding machine developed by FiatAvio has been modified to obtain the face gear tooth surface as the envelope of standard involute spur gear (shaper) against the face gear surface.

The achieved quality standard after grinding has been AGMA class 12, considering spur gear standards as a reference, as no standard is available for face gears.
A surface roughness of 0.4 µm Ra has been achieved.

For the dimensional inspection of the topography of tooth surface, an approach similar to the inspection of spiral bevel gears has been adopted, i.e.:

- surface of the tooth has been defined by 3D surface modelling;
- a grid has been selected on the surface;
- deviations of the actual surface with respect to the reference surface have been measured in the selected points; the typical output is the topograpy shown in **Figure 7**.

Figure 7: *Face Gear topography inspection output*



Rig testing

Two face gear modules have been tested in a back-to-back arrangement, i.e. the face gear of one gearbox (test gearbox) drives the face gear of the other gearbox (slave gearboxes), the two gearboxes are connected to the rig to close the torque path (closed loop arrangement). The operating torque is then applied to the gear system.

Input power to run the drivetrain is provided by a 550 kWatt electric motor.

The following instrumentation may be connected for data storage and analysis:

- 6 pressure probes;
- 60 temperature probes;
- 6 oil flow mesurements;
- 6 accelerometers.

The following test sequence has been applied:

- run in for 3 hours at relatively low torque;
- 150 hours at 265 kWatt;
- 30 hours at 371 kWatt.

At the end of the run in, a satisfactory tooth contact pattern has been found therefore allowing to continue with the foreseen test program.

The overall number of cycles accumulated by test components has been reported in the following **Table 3**.

Table 3: *Summary of teeth cycles (millions)*

	150 h/ 265 kWatt	30 h/ 371 kWatt	Overall
Input pinion	108	21.6	129.6
Torque split face gear	12.1 (*)	2.4 (*)	14.5 (*)
Recombining pinion	54 (*)	10.8 (*)	64.8 (*)
Output torque face gear	24.2	4.8	29

(*) *Reverse bending*

The gearboxes have run smoothly with an even split of the torque.

The inspections of gears after 150 hours and at the completion of the test campaign have shown a satisfactory tooth contact pattern both on face gears and on the spur pinions, no significant difference has been observed between the tested gears.

The face gear tooth flank, that is shown in **Figure 8**, is characterized by:

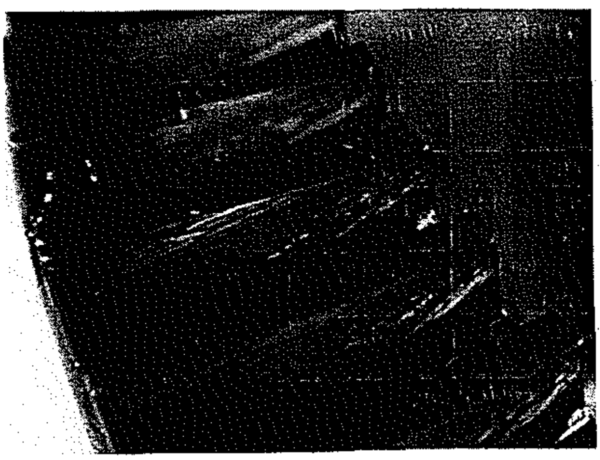
- a well spread contact pattern, apart from the outer radius;
- some micropitting at the inner radius and at the root of the flank, close to the undercut area, has been found.

To cope with these effects, a further optimization step of the face gear and pinion geometry (2nd order) is needed, following an approach similar to the optimization of the contact pattern in bevel gears. The corrections of the gear topographies should aim at:

- movement of the contact on the face gear flank torwards the outer radius;
- relief of contact in the area close to the face gear flank undercut.

Of course the increase in the gear ratio would facilitate this optimization task.

Figure 8: *Contact pattern on the face gear after test*



4. CONCLUDING REMARKS

The architectural feasibility studies have highlighted potential benefits achievable by introducing face gear technology based on the split of the torque to the helicopter Drive Train in terms of mass, recurring cost, reliability and cost of ownership. Several options are available to split the torque, depending on the Drive Train architectures.

Our internal technology readiness program has resulted in design and manufacturing (including grinding) of 11" diameter, Pyrowear 53 material, case hardened face gears. The manufactured components have been sucessfully tested in a split torque arrangement for 150 hours at 100% power rating (i.e. 265 kWatt) and 30 hours at 140 % power rating. A satisfactory tooth contact pattern has been achieved.

On the basis of the performed activities, the areas where further development is needed on face gears are:

- standard design approach for gear analysis;
- design and manufacturing integration for tooth contact pattern optimization, similarly to what is done for bevel gears;
- manufacturing process to allow production of large volumes at cost effective machining times.

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