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**“FACET”: Face Gears in Aerospace Transmissions**

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# “FACET”: Face Gears in Aerospace Transmissions

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## ABSTRACT

The BRITE-EURAM Programme FACET “The development of face gears for use in aerospace transmission “, that started on February 1998, has now completed its first and a half year of researches.

The project is coordinated by GKN Westland Helicopter Limited (UK) and involves Agusta (I), Eurocopter (F), ZF Luftfahrttechnik GmbH (D), ZF Friedrichshafen AG (D), INSA Lyon (F), Politecnico di Milano (I), WZL-RWTH Aachen (D) and Reishauer AG (CH).

The scope of the project is to investigate the application of face gears in aerospace transmission instead of bevel gears and therefore to ascertain the real advantages of such kind of gears, in terms of reduced gear stages, reduced weight and noise, reduced cost and increased reliability, taking into account the limitations imposed by the face gears technology.

The project, which will last 42 months, is composed by four tasks concerning architectural studies, preliminary investigations, full scale tests and design review and guidelines. In the first year and a half the work has concentrated on the architectural studies, on the theoretical aspects related to geometry, kinematics, stresses and manufacturing, on the manufacturing and first tests of laboratory gears and on the definition of full scale tests, including the design of the test rigs.

## 1. INTRODUCTION

The aim of investigation and a description of the FACET programme, including an overview of the main contributions of the Partners involved, have been presented in a previous Paper [1], and are briefly summarised.

As all helicopter transmission configurations include at least one gear stage which turns the horizontal drive from the engines to the vertical for the main rotor, face gears provide an attractive solution to replace the spiral bevel gears that are presently used for this purpose. Face gears use conventional involute pinions which drive flat wheels with highly corrected involute tooth forms (Figure 1).

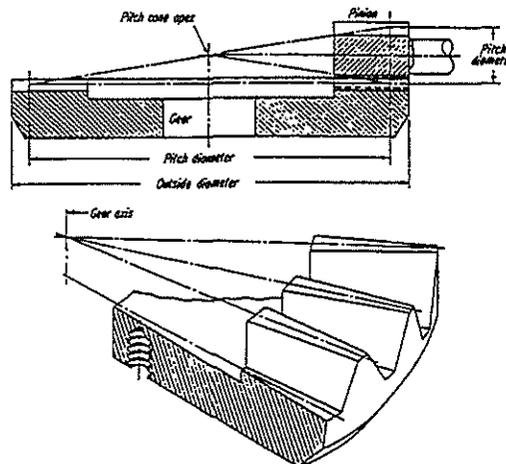


Figure 1: Face gear arrangement (source: D.P. Townsend, 1992)

They have been used for many years in some industries, but they need an improvement, especially concerning the development of an efficient industrial method for grinding after hardening, in order to meet the high standard of accuracy and load capacity required for aerospace applications.

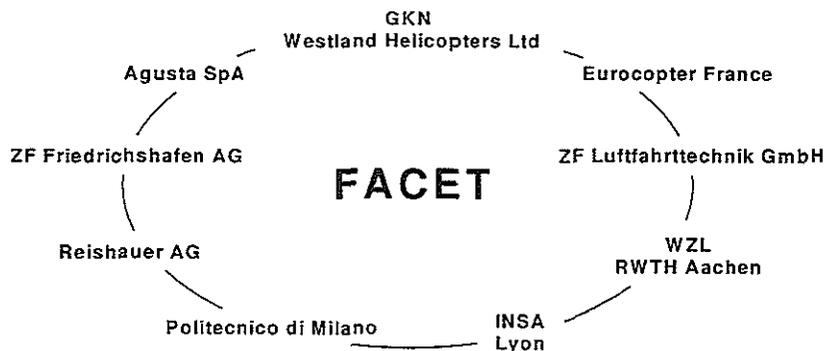
The research activities of the FACET programme will concentrate on the development and experimental validation of design tools for face gears and of a manufacturing procedure which enables face gears to be produced to the required standards of accuracy. The real opportunities offered by face gears technology for adopted changed configurations in helicopter and other aerospace transmissions will be assessed by means of analyses and tests, aimed at defining the limiting design and operating parameters of face gears. Innovative configurations with a reduced number of gear stages, a reduced gearbox weight, a lower manufacturing and assembly cost consequent to a less critical alignment, an increased reliability and reduced maintenance costs are the main expected advantages.

## 2. FACET PARTNERS

The FACET consortium is coordinated by GKN Westland Helicopter Ltd (UK) that is one of the major helicopter manufacturing companies in Europe and includes two other helicopter manufacturers: Agusta (I) and Eurocopter (F).

The other industrial partners are ZF Friedrichshafen AG (D), a german company leading in design and manufacturing of transmission systems, ZF Luftfahrttechnik (D) and Reishauer AG (CH), a swiss machine tool manufacturer, specialising in the production of grinding machines extensively used in the aerospace industry.

The consortium includes three academic partners: WZL (Werkzeugmaschinenlabor) RWTH Aachen (D), a research institute specialising in gear research, and in particular in all gear production processes, including cutting machines, gear calculation, simulation of generation, load capacity and running behaviour investigations. INSA (Institut National des Sciences Appliqueés) Lyon (F), which is involved with the CASM laboratory, that is experienced in the simulation of mechanical behaviour of mechanical systems and has a relevant background in gear transmissions. Politecnico di Milano (I), an Italian Technical University, which is involved with the Dipartimento di Meccanica, that is experienced in the fields of power transmissions and of fatigue.



*Figure 2: FACET Partners*

### 3. DESCRIPTION OF THE FACET PROGRAMME

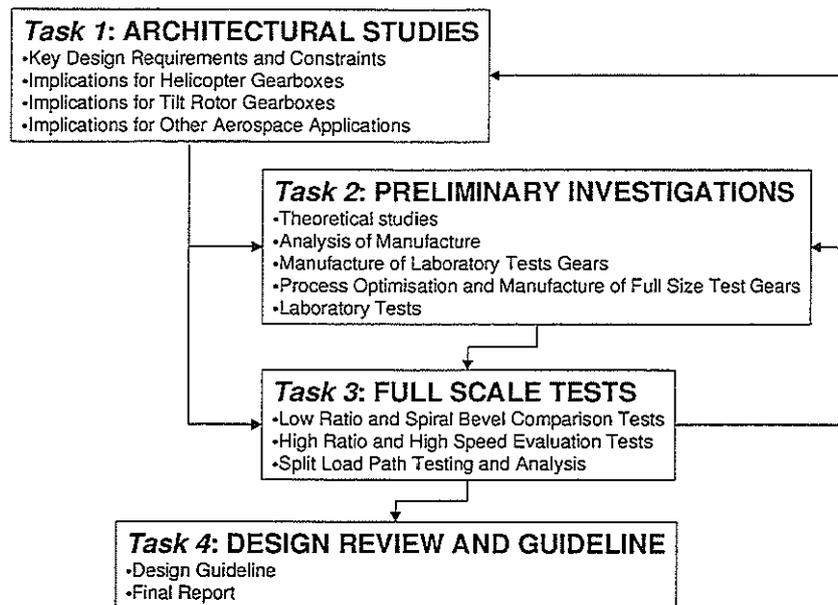


Figure 3: The FACET programme flow chart

Figure 3 shows the key issues of the FACET Programme. Task 1, that has been named *Architectural Studies*, deals with the definition of the requirements for face gears and with the investigation of new architectures for aerospace applications that could be made possible by face gears development. In more detail, the key design requirements and constraints for aerospace applications will be identified and the implications for helicopter and tilt rotor gearboxes will be evaluated. The possible use of face gears in other aerospace applications will also be considered. This phase of the programme will be coordinated by GKN-WHL and will give the necessary input to Task 2, named *Preliminary Investigations*, that will provide the computational tools to support the design of face gears. This part of the Programme includes theoretical studies in order to generate tooth profile data, to model gear meshing interaction and to simulate the gear manufacturing process. A detailed analysis of machining process will be performed and simulation of preliminary hobbing and gear finishing operations will enable the manufacturing process of full size test face gears to be optimised. Laboratory tests will be performed in order to evaluate load sharing, scuffing and pitting resistance of face gears. Moreover, gear error and noise tests will be carried out. Comparison will be made with spiral bevel gears. Task 2 is coordinated by ZFF.

Task 3, that is coordinated by ECF, involves the three helicopter manufacturers (Agusta, ECG, GKN-WHL), each undertaking a *Full Scale Test*, corresponding to a particular aspect of face gear operation. "Low ratio" face gears will be tested and performance compared with spiral bevel gears. High ratio and high speed face gears will be tested in order to evaluate optimum performance in a helicopter gearbox environment. Finally, split load path testing will be performed to evaluate the ability of face gear designs to split the input torque in equal parts, taking into account pitch errors, shaft and wheel deflections and casing flexibility.

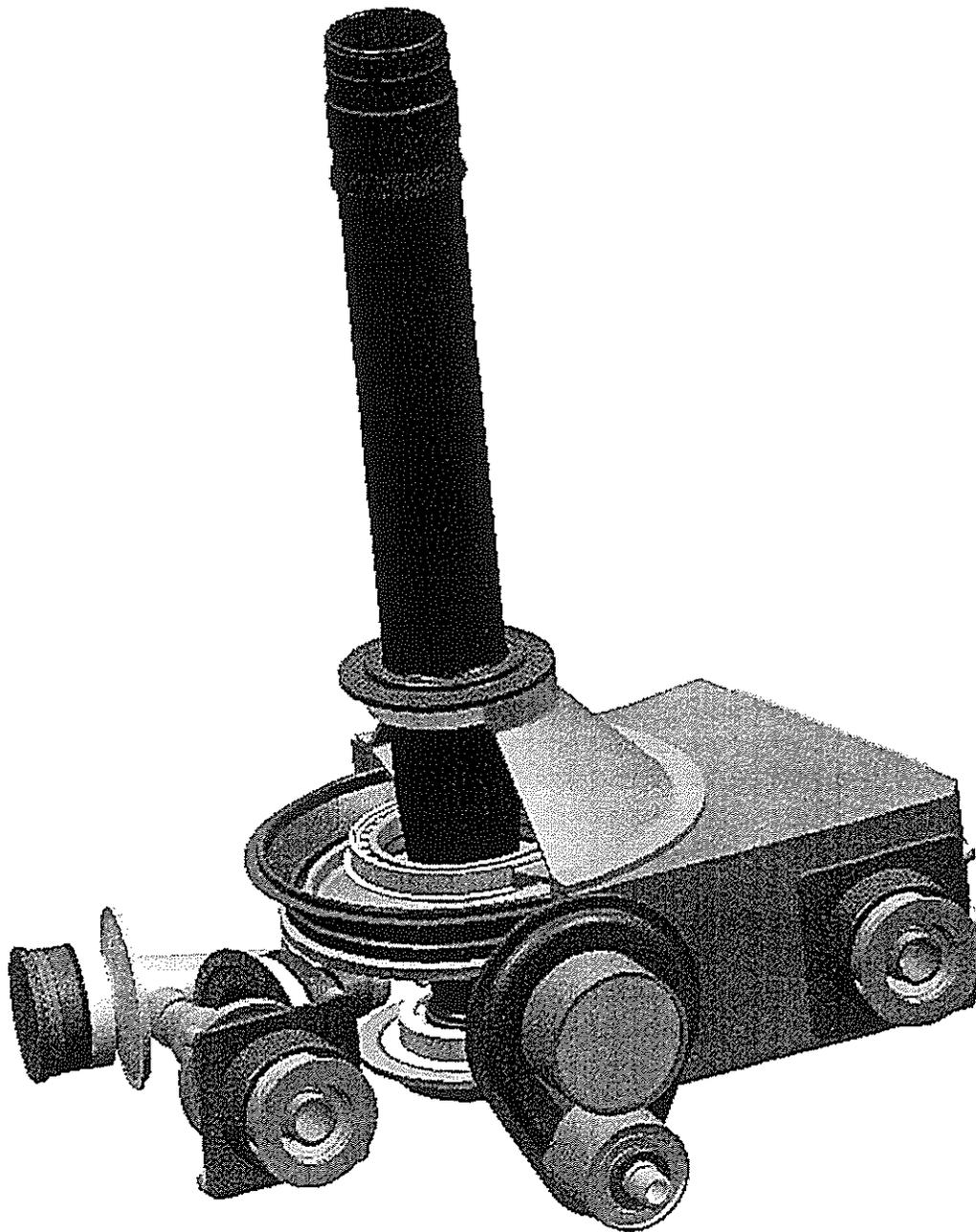
Task 4, *Design Review and Guideline*, is coordinated by GKN-WHL and is the final part of the programme; this will involve a detail analysis of the previous work and production of a technical design guideline that will enable aerospace transmissions designers to get full benefit of optimum face gear designs. The final report will summarise the work undertaken in order to promulgate the results to the EC and industries involved in transmission design and manufacturing.

## 4. PROGRAMME PROGRESS

### 4.1 Architectural Studies

In the task devoted to architectural studies, the helicopter manufactures and ZFL, coordinated by GKN-WHL, have identified the main design requirements and constraints and have selected the Face Gear configurations for further studies.

In particular the implications for helicopter gearboxes will be investigated by Agusta which will consider a twin engine light weight helicopter transmission design with face gears. A conventional three stage MGB design will be used as a reference while two stage configuration feasibility will be explored. In particular, Agusta will a new “radial split” configuration concept (Figure 4).



*Figure 4: “radial split” configuration for helicopter MGB*

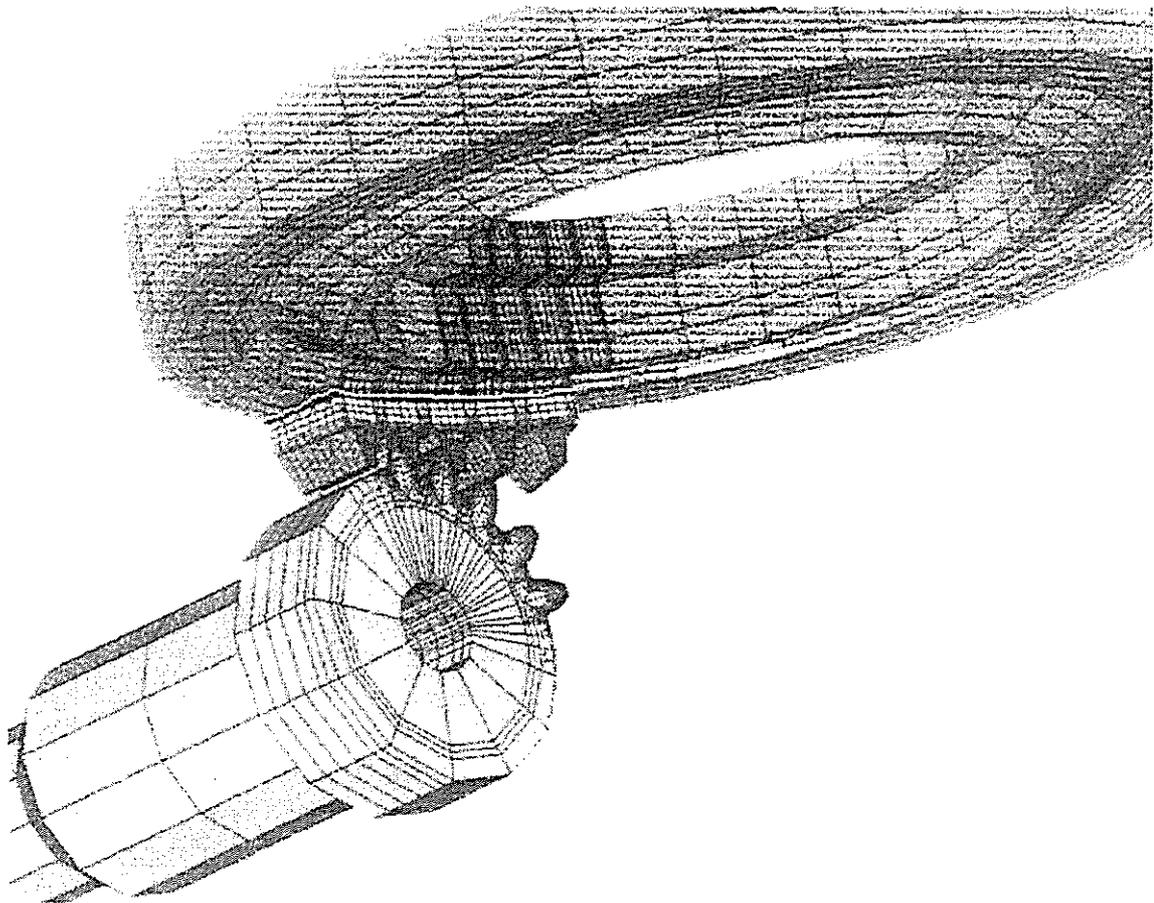
The implications for Tilt Rotors will be investigated by ECF which has selected a 1200 kW range Tilt Rotor Aircraft. Two different engine installation have been identified and for each, two gear train configurations will be analysed.

Concerning the implications for other Aerospace Applications, ZFL, after the examination of several possibilities to modify an existing gearbox by using face gear technology, has identified a right angle gearbox for use in a flap actuating system, in which the face gear will replace the existing bevel gear.

#### 4.2 Preliminary Investigations

In the subtask concerning theoretical studies, INSA has completed the work related to the geometry definition of spur and helical face gears by extending the theoretical method developed by Litvin in order to include practical cases and helical face gears and has developed a software. The kinematics simulation has been performed on the basis of Litvin TCA method, which has been adapted according to the geometry definition and has been extended to the case of line contact. The software developed for TCA can analyse both aligned and misaligned face gears.

ZF and GKN-WHL have performed a non-linear meshing analysis of face gears by using two different methods (an explicit FE code for WHL and an implicit one for ZF) in order to determine the tooth pattern displacement and the stresses in the face gear and pinion, taking into account all deformation effects and gear corrections (Figure 5 and 6).



*Figure 5: ZFF laboratory test gear set in mesh position*

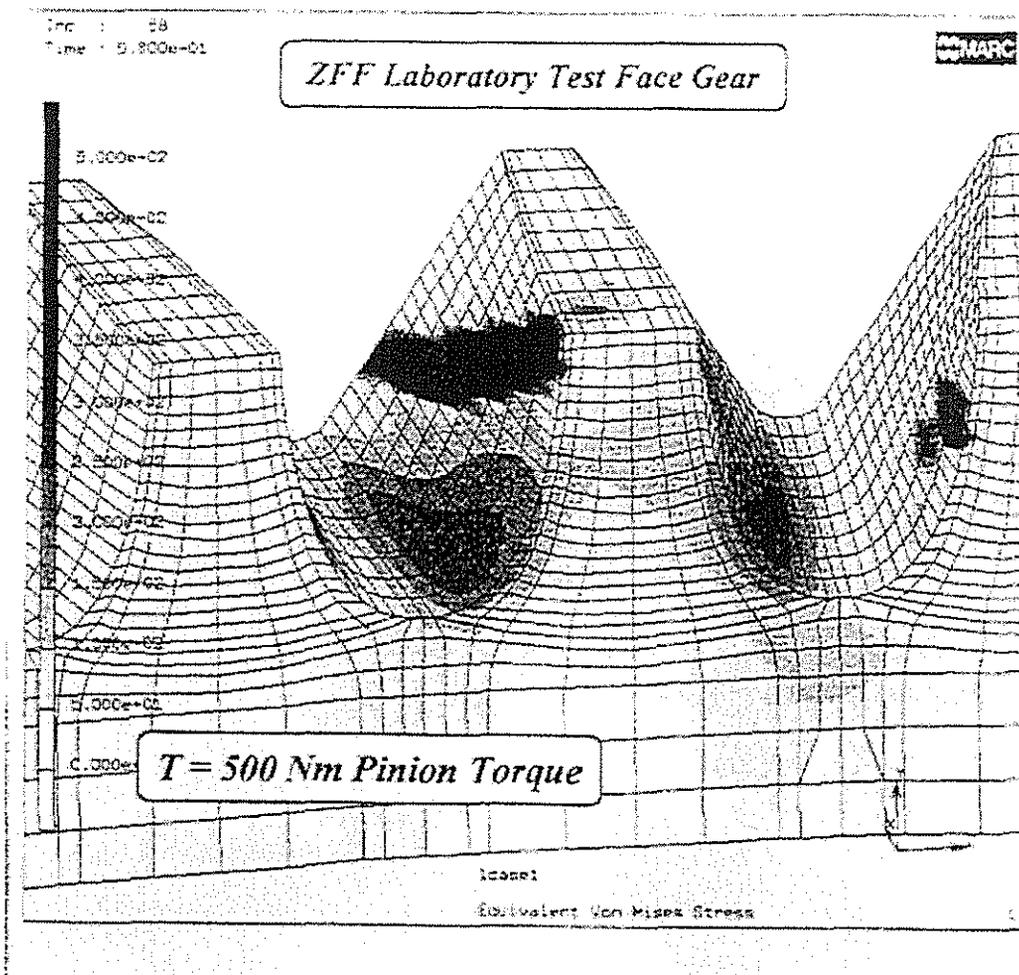


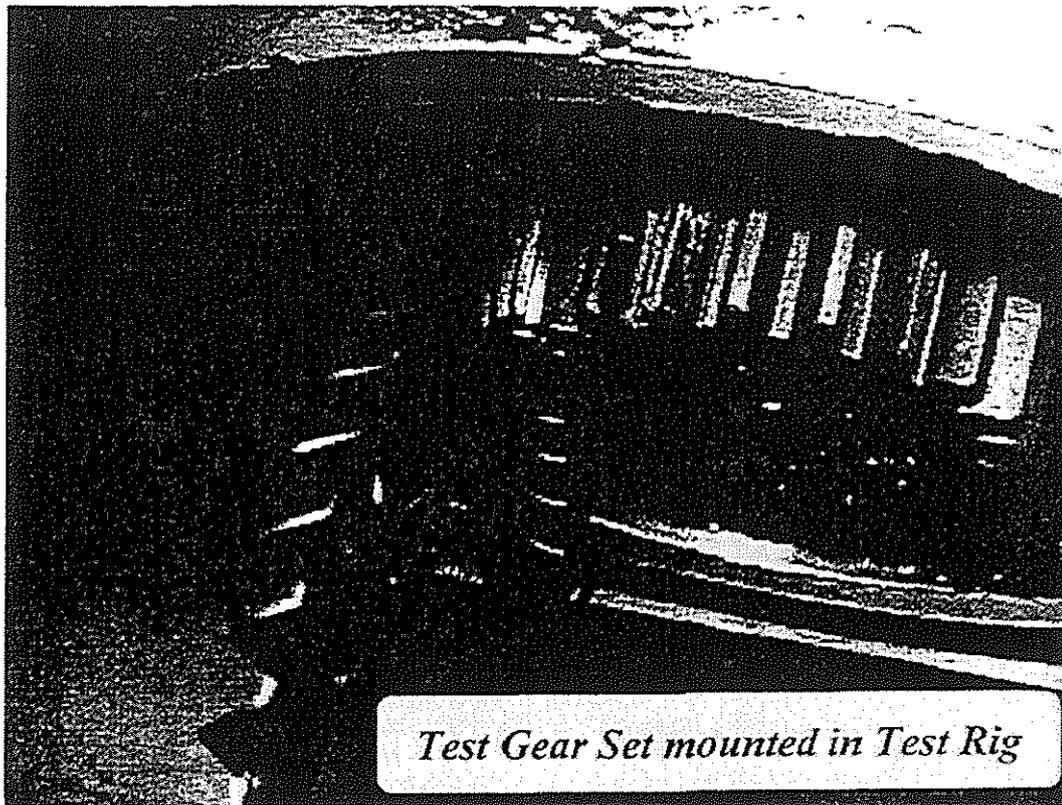
Figure 6:  $\sigma_{Mises}$  ZFF laboratory test face gear

In the subtask concerning the analysis of manufacture ZF and INSA have developed the design of the laboratory test face gear and consequently of the shaper cutter, while WZL have developed a manufacturing simulation software which can generate the shape of different cutting tools and the effect of different machines and processes or of modified settings on tooth flank topography. The software is suited for simulation of spur face gear (with and without offset) and for helical gears. A module to generate tooth flank xyz co-ordinates for measuring and comparison purpose has also been developed.

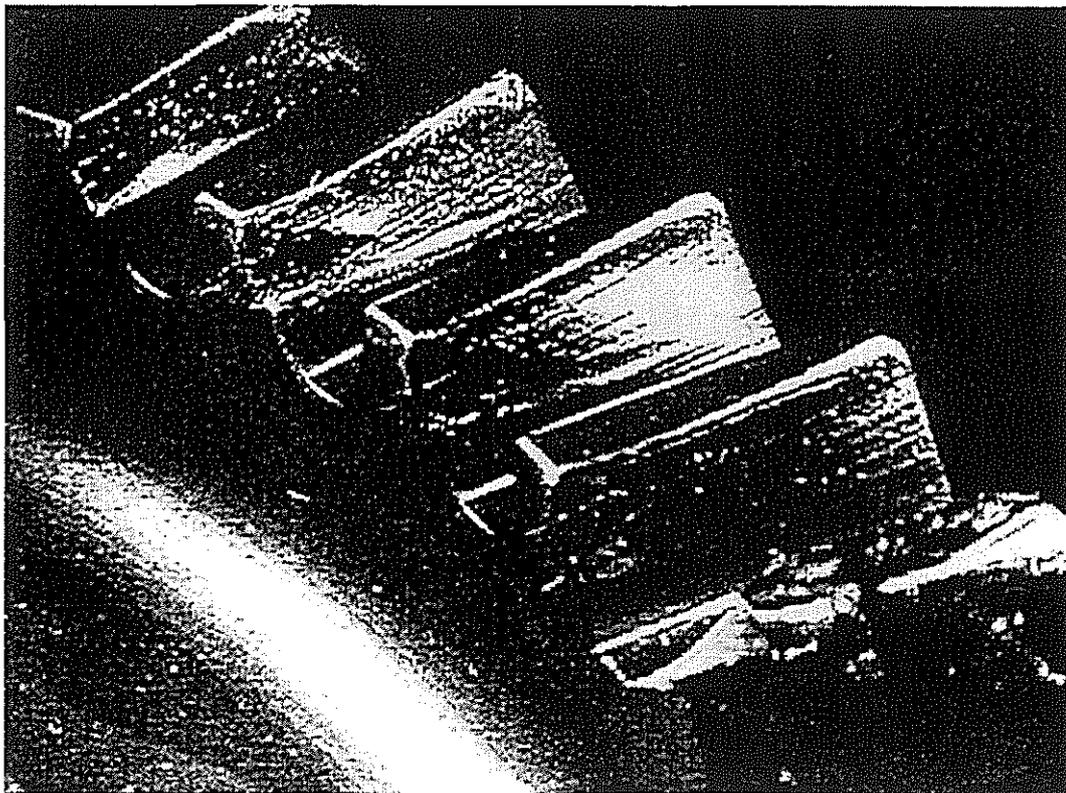
In the subtask devoted to test gear manufacturing both test pinion and test face gear have been manufactured. Test pinion were hobbed, case hardened, ground and shot peened, while test gears were soft shaped, hardened and skive shaped. A quality inspection software to generate files for ZEISS machine have also been created.

In a specific subtask Reishauer has developed a special grinding head for face gears to be fitted to an existing grinding machine. The grinding head is suited to grind face gears up to 5 mm module and 400 mm outside diameter. A new dressing method has also been developed for the profiling of the special grinding thread.

The last subtask of preliminary investigations has concerned laboratory tests and has been performed by ZFF. In particular the first test activities have regarded contact pattern test, failure load test, strain gauge measurements to verify and calibrate FE models (Figures 7 and 8).



*Figure 7: ZFF laboratory test gears mounted on test rig*



*Figure 8: Picture of failure load test*

The face gear transmission tested is composed by a 19-tooth spur pinion, 4 mm module, 20° pressure angle, meshing with a 53-tooth face gear, 240 mm outer diameter.

#### 4.3 Full scale tests

A pre-design method for sizing face gears has been defined in order to design and analyse the architecture of the test rigs. The pre-design method has been applied to the design of the three face gears of the full scale tests. After verification of the machining and gearbox constraints, test philosophies and preliminary test programmes have been defined. Consequently to the test philosophies test rigs arrangements have been designed.

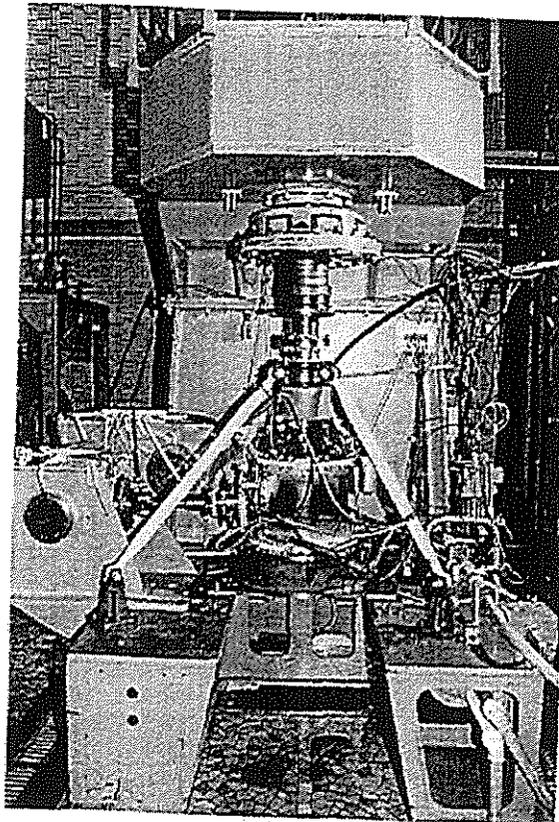
##### *Test 1 – Low Ratio Full Scale Test to determine the intrinsic performances of Face Gear/Spiral Bevel Gear*

In this subtask, ECF will analyse tooth corrections and sensitivity through dynamic tooth pattern test and will investigate the performances in terms of endurance, fatigue and lubrication through endurance tests (100 hours).

The face gear transmission is composed by a 17-tooth pinion meshed with a 61-tooth gear, corresponding to a ratio 3.59. The relevant pinion data are: normal module 4.6732 mm, normal pressure angle 25°, shaft angle 87°, helix angle 10°. The face gear has a 323 mm outside diameter, and a 28.79 face width.

The operational data are a input speed of 6000 rpm and a power of 440 kW, corresponding to a pinion torque of 700 Nm.

Figure 9 shows a picture of the test rig.



*Figure 9: ECF test rig*

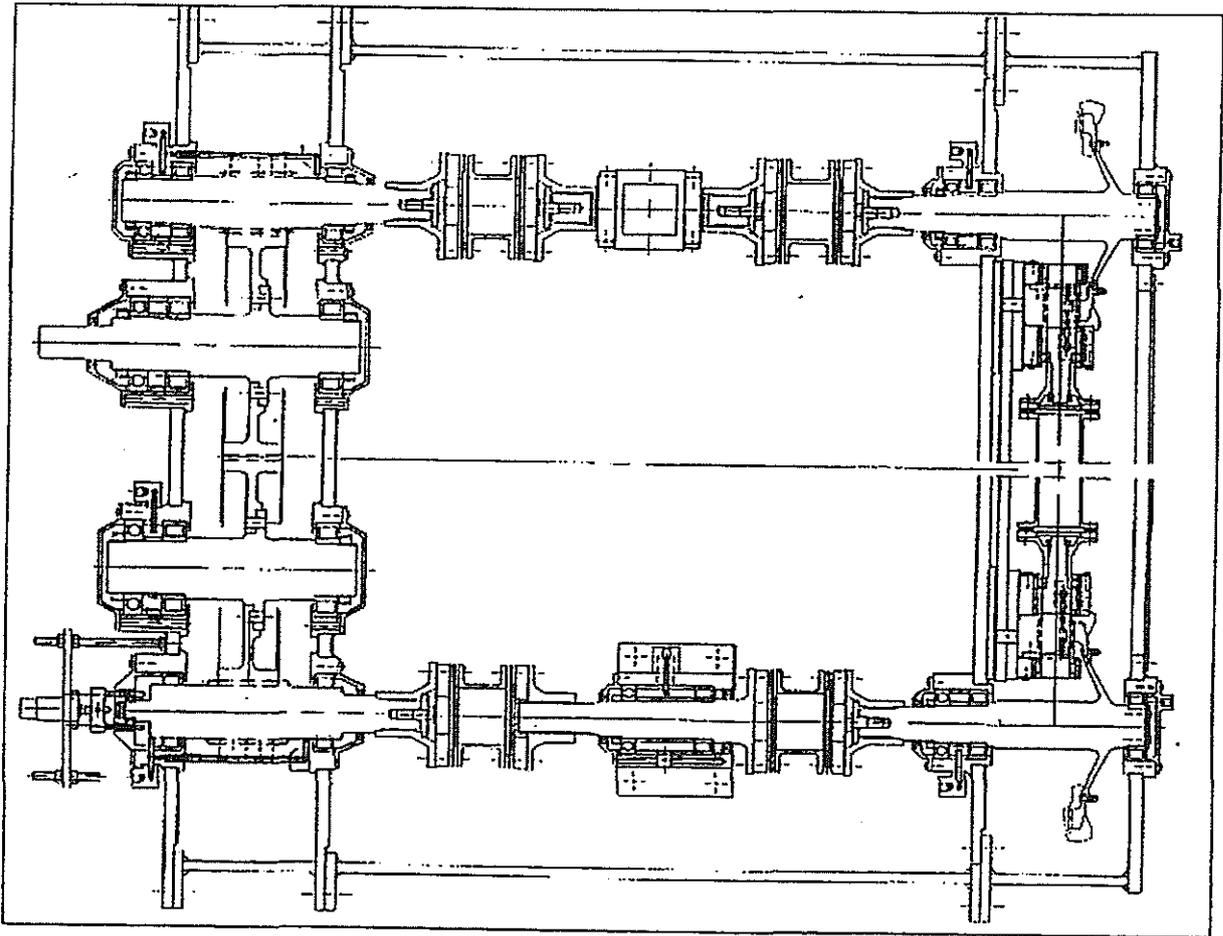
*Test 2 – High Ratio and High Speed Full Scale Test to determine the optimum operating performance of high ratio at high speed and validate design tools*

The objectives will be reached with the following tests:

- pattern development, static and dynamic test
- vibration and noise measurements under dynamic test
- fatigue test
- scuffing test and temperature measurements

The test rig to perform the planned tests has been designed and a drawing is represented in Figure 10.

The test data are: nominal input speed of 21000 rpm (maximum input speed 30000 rpm), minimum ratio 6:1, minimum module 3 mm, 320 mm outside face gear diameter, 20° pressure angle, 90° shaft angle, 0° helix angle and 0 mm offset.



*Figure 10: GKN-WHL High ratio test rig schematic*

*Test 3 – Split Load Path Full Scale Test to determine the ability of Face Gear design to split torque.*

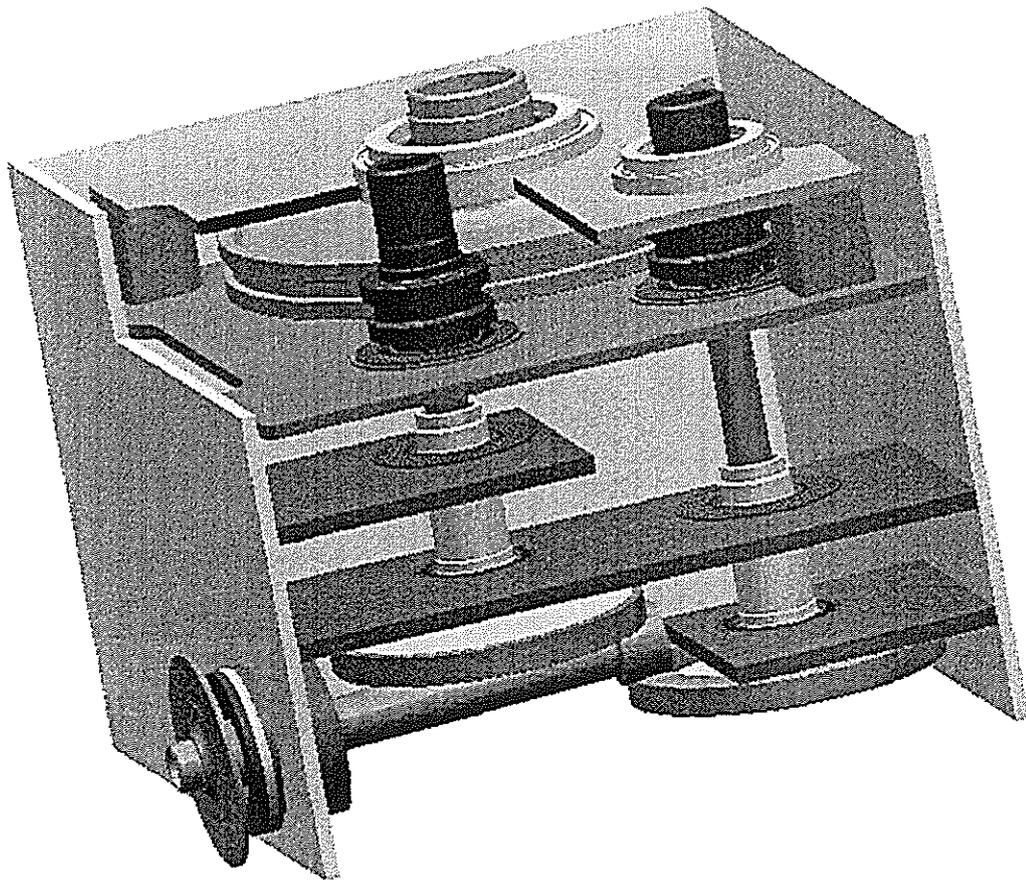
The purpose of the test is:

- to show that the input torque is split equally between the two face gears
- to estimate the dynamic effect as the input shaft passes and operates above its first natural frequency
- to estimate the effect of increased backlash on torque splitting

The following measurements will be performed:

- Torque splitting measurements
- FACE gears stress measurements
- Vibrations / resonances
- Temperature measurements
- Deflections

The test gearbox architecture is represented in Figure 11 and Figure 12 shows an FE model of the test rig.



*Figure 11: Agusta test rig architecture*

The test rig operating features are:

- Open loop, electric recirculating power
- 500 Hp
- Input speed 6100 rpm
- Output speed 367 rpm
- Gear ratio 16.6
- External oil circuit (Oil flow and temperature control)
- Provision to increase operating gear backlash

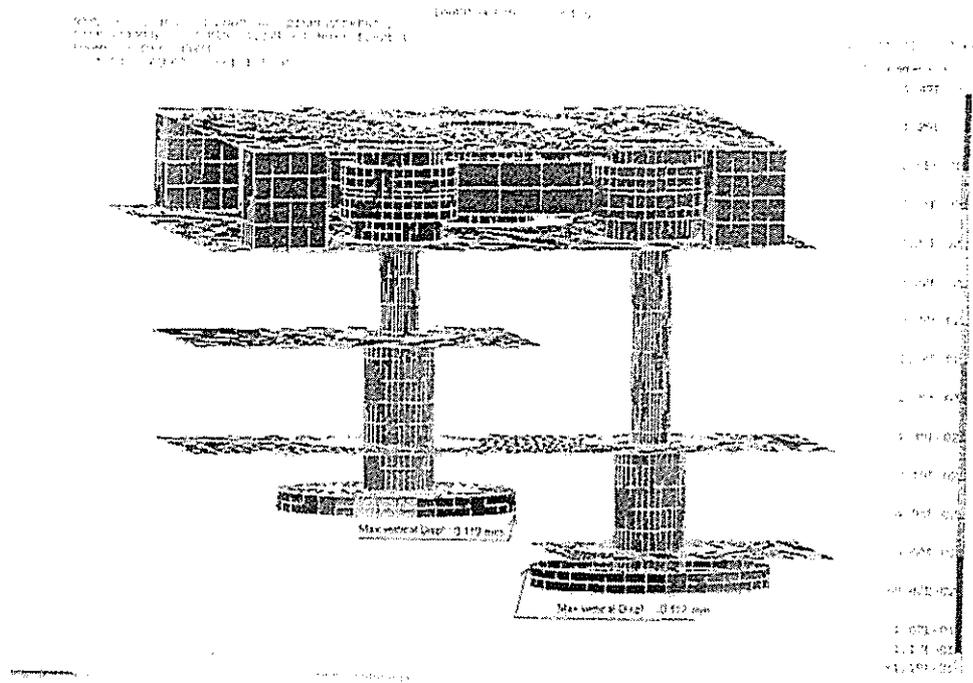


Figure 12: FEM model of Agusta test rig

## 5. CONCLUSIONS

The FACET programme will identify the advantageous aerospace applications for face gears. The research activity, which involves the main European helicopter manufacturers, a leading transmission systems manufacturer, leading academic establishments and a machine tool manufacturer, will provide an experimentally validated procedure for the design and manufacture of ground face gears for aerospace applications. Face gear technology should enable the European aerospace industry to design and manufacture transmissions that are lighter, quieter, more reliable and at the same time cost effective.

## 6. ACKNOWLEDGMENTS

Authors would like to acknowledge all the partners of the FACET programme and the EC for permission to publish this paper

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