# VIRTUAL MAIN GEAR BOX CONCEPT MEANS FOR DEVELOPEMENT CYCLE REDUCTION AND ENHANCED PERFORMANCE

**By**

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**Abstract**

*The gearbox is one of the most important helicopter components in terms of development, manufacture, and maintenance costs. Furthermore, the economical constraints of today's markets entail short development cycles, low production costs, enhanced performance and high reliability.*
*However, the technologies employed for the older generation helicopters are no longer able to satisfy these new requirements.*
*Over the last ten years, EUROCOPTER has therefore developed a new design & development technique, called the "Virtual MGB Concept".*

*This paper presents a concrete application of this virtual MGB concept, as it was used to develop the MGB for the new Super Puma EC225/725 version. The resulting reduction in the development cycle and improvement in performance are also detailed.*

## 1 – INTRODUCTION

Not only is the gearbox one of the heaviest components of a helicopter, but it is also one of the most important in terms of development, manufacture, and maintenance costs.

The economical constraints of today's markets imply short development cycles and low production costs. However, this situation is compounded by increasingly severe regulations, and by requirements for enhanced performance and reliability, and lower maintenance costs.

Although the 52 million flight hours accumulated over almost 50 years represent a considerable pool of experience for the new gearbox designs, the technologies employed for the older generation helicopters are no longer able to satisfy these requirements.

Over the last ten years, EUROCOPTER has therefore been developing a new design & development technique, called the “Virtual MGB Concept".
This gearbox concept is based on intensive simulation and computations that cover:

- **Geometric modeling**. The gears, shafts, and casings are modeled in 3D using CATIA® software. The aim is to optimize the overall process up to and including programming and machining, by computer aided design, i.e. geometric modeling for simulation and computational applications,

- **Gears**. The running patterns for both spiral bevel and spur gears are simulated and optimized under load, with allowance for the deformation of casings, web elasticity and geometric defects. In addition, these tools are used for determining the setting parameters for gear tooth grinding, thereby ensuring accurate and rigorous production of the tooth flanks defined by simulation.

- **Bearings**. The load and pressure distributions on rolling elements are analyzed, with allowance for the deformation of casings and shafts, the assembly conditions and the temperature gradients. The aim is to optimize the internal geometry with respect to the operating conditions.

Whenever a new MGB is developed, the various tools in the virtual MGB 'toolkit' are put to full use because projects are being scheduled closer and closer together in the 'always tense' development timetable.

This experience gained helps to improve and optimize the overall process.

We will now demonstrate the benefits of the virtual MGB concept, by comparing its application in the development of the EC225/725 MGB with past development work on other MGBs. In fact, the concept has resulted in performance gains, lower risk levels, and shorter cycles. This is particularly true for the development of gear tooth contact patterns, as the development tests now merely consist in validating the virtual "right-first-time" development results.

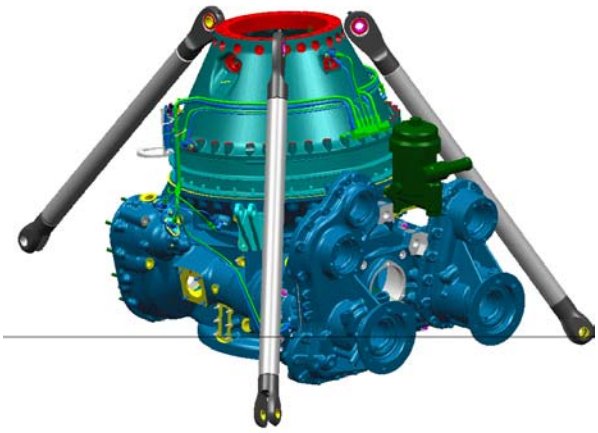
## 2 –EC225/725 Main Gearbox

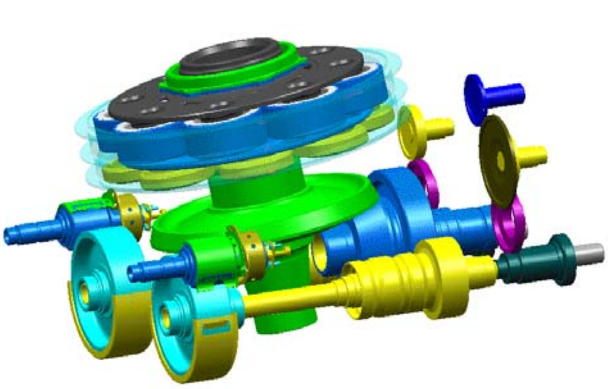
### 2.1 General Description

The MGB is designed to transmit the power developed by the engines to the helicopter consumers, which, apart from the main rotor, are identical to those of 332 MKII.
The MGB is a 332 MKII MGB that has been upgraded to 2,600 kW at max. take-off power with two engines. The single engine power is also upgraded.
As far as the MGB is concerned, the EC225 specifics compared to 332 MKII involve:

- Increasing the power spectrum values: Max. Take-Off Power (MTOP), Max Continuous Power (MCP), One Engine Inoperative (OEI) and transients
- Increasing servo loads
- Meeting JAR 29 resistance requirements after oil has been leaking for 30 minutes.

The MGB includes a main module, an epicyclic module, a bevel casing module, and accessory modules.





One of the main differences between the 332 MKII and the EC225/725 MGBs is the bevel gear drive.

In fact, the margins measured in the 332 MKII tests demonstrated that the gears were able to withstand the increased EC225/725 power - apart from the main bevel gear drive, whose margins were insufficient for surface fatigue.
Scuffing was detected during 332MKII development tests at high power levels.

The power increase for the EC225/725 entailed:

- Changing the material and the heat treatment. Case-hardened 16NCD13 was replaced with deep-nitrided 32CDV13 as the main bevel gear drive material.
- Grinding the surface of the bevel gear drive teeth: tooth contact pattern development.

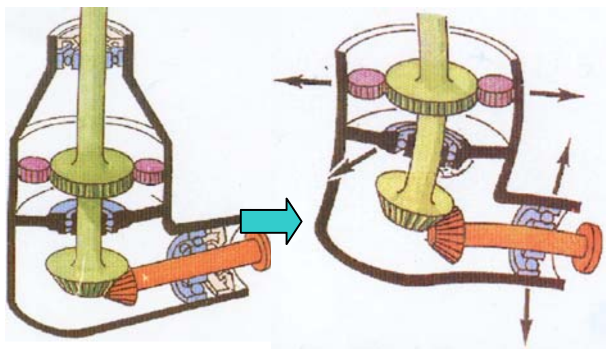
## 3 –TOOTH DEVELOPMENT

### 3.1 Objective

The main function of the MGB is to transmit the power from the engine(s) to the rotor, and to reduce the rotational speed input to the rotor.
The operation obeys the well-known law Power = Torque x ω
The power input P to the MGB is constant (ignoring losses). This means that, when the torque T increases, the rotational speed ω decreases at the rotor.

For example, the input speed for the EC225/725 is 23,000 rpm, and at the main rotor 265 rpm, for a maximum input power of 2,600 kW. This produces a torque of 540 Nm on each MGB input, and an MGB output torque of 80,000Nm!

These magnitudes generate extremely large transmission loads. The casings carry these loads and are deformed - all the more so because they are made of light alloys. While aluminum and magnesium alloys have a low specific gravity, they unfortunately have a low modulus of elasticity.



The casing deformations can reach several millimeters. They interfere with the functioning of the mechanical contacts, which in service immediately leads to flaking and scratching on the teeth.

***Flaking on Spiral Bevel Gear Teeth***

One possible solution would be to counteract the deformation by stiffening the casings. However this would result in a prohibitive increase in weight.

The other solution is to adapt to these deformations, by adjusting the contact areas and grinding them in order to eliminate the local overloads when running. Roughly 10 microns of material have to be removed. This solution therefore consists of developing the tooth contact pattern.

This has proven to be one of the longest and most difficult phases in MGB development. This is particularly so for spiral bevel gears, like those of the EC225/725. The reasons are the very complex shape of these gears, their sensitivity to deformation-induced position errors, the accuracy required for optimum contact.

### 3.2 Conventional Method

Contact patterns for the MGB are usually developed experimentally on a test bench.

The teeth are coated with varnish when the MGB is being assembled. In the test, the MGB is run at progressively increasing power levels. The resulting contact patterns are then examined at each load level. The corrections needed are defined - or rather 'guestimated' - and incorporated by grinding the tooth surfaces. The process is continued until satisfactory contact patterns are obtained under full load.

We will illustrate this process by an example. In 1975, the development of the MGB spiral bevel gear teeth on the 332 MKI entailed 15 runs on the test bench over a period of 9 months, in order to produce the so called "developed", but not optimized, teeth.

In practice, this experimental method is both time-consuming and very expensive in terms of the assembly, disassembly, inspection, and grinding cycles. Moreover, this process is necessarily in an advanced phase of manufacture. Without any control of the parameters affecting the contact pattern (e.g. the deformation), this method remains approximate. Moreover, it provides no guarantee before testing that the proposed corrections will prove successful. Indeed, there is a high development risk, plus the fact that it is impossible to control the development cycles. Clearly the method is not adapted to the requirements existing today.

### 3.3 Virtual Development Tools

The key to solving these problems was twofold: first, to be able to control the definition of the teeth surfaces before and after adjustment; and second, to simulate gears under load, including the position errors generated by casing deformation.

In the 1980s, simulation tools were developed with the help of the INSA CASM laboratory in Lyons. These tools were in fact the very first virtual MGB development tools:

- Geometry and Simulation of spiral bevel gears (SPIRO (1) software)
- Simulation of the deformation of casings under load (ASSYM (2) software)

***SPIRO Software***

The operating sequence of the grinding machine is specified analytically in equation form, and then integrated in SPIRO. The software then reproduces spiral bevel gear tooth surfaces that are similar to the surface generated by the grinding machine. The complete geometry of several pinion and gearwheel teeth is then generated based on this surface, and the gears simulated. The torque loading is introduced, and the contact patterns are simulated under load during meshing. It is then possible to introduce the position errors - caused by geometric defects and deformations - of the pinion relative to the gearwheel,.

***ASSYM Software***

This software was developed to simulate the overall behavior of the MGB under static loading. The pinions, bearings, casings and shafts are all integrated. The main goal is to determine the relative displacements on the gearing and bearings.

ASSYM has the following main advantages:

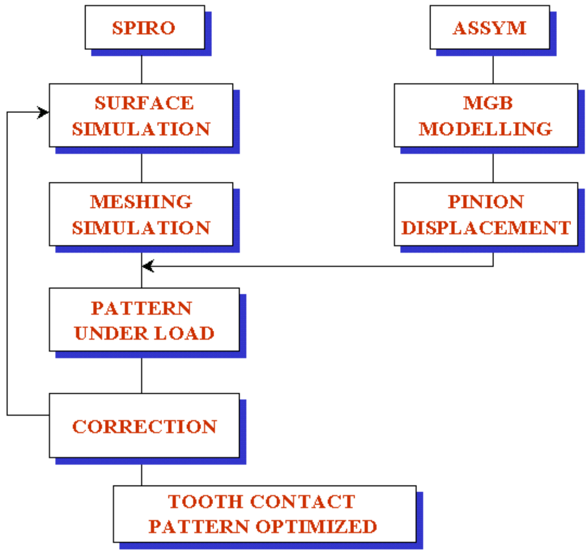
- It simultaneously allows for the stiffness of the casings, and the stiffness and non-linearities of bearings and pinions.
- The overall model can be used in a flexible manner because macro-elements (super geometric models) are available. The macro-elements are in condensed stiffness matrix form, and are assembled together via the contact and linking elements (gearing, bearings) in the MGB.
- Shorter computing times (a few minutes), because this modeling architecture uses macro-elements condensed in an overall stiffness matrix format.

***Virtual Tooth Development Principle***

The principle applied for virtual development of teeth is first to determine the position errors induced by deformation (computed by ASSYM). This data is then entered in SPIRO to simulate the contact patterns under load and deformation. The next step is to "virtually" correct the contact patterns with the "grinding machine" parameters until optimized bearings surfaces are obtained. The optimized tooth surface is then generated as data files containing:

- the grinding parameters that will accurately reproduce the simulated surface,
- the geometry that will act as the reference for the production quality control.

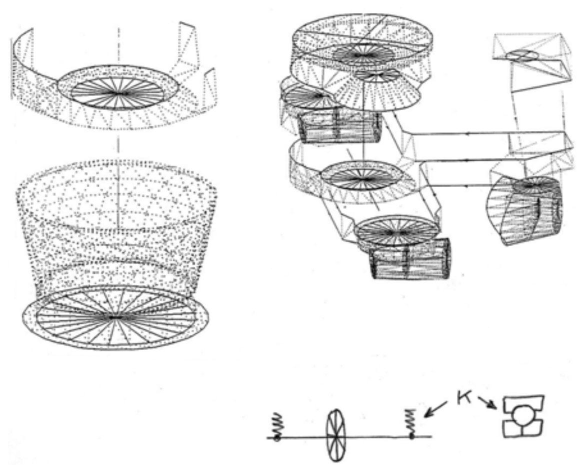
After the assemblies have been manufactured, the final adjustment will be validated by an actual test on the MGB.




## 3.4 <u>Initial Steps in the Virtual Development Process</u>

***In 1990, Development of the Tiger MGB***

The method was applied for the very first time in the development of the Tiger MGB in 1990. At this time less computing power was available than today. The MGB structural components - casings, shafts, pinions, etc. - were modeled using plate, beam and bar elements. The bearings were modeled by variable-stiffness springs, and the gearing by contact elements.
Although the model simplifies the geometry, it nevertheless represents the stiffness with quite good accuracy.




The relative displacements of the pinions computed by this model were then input into

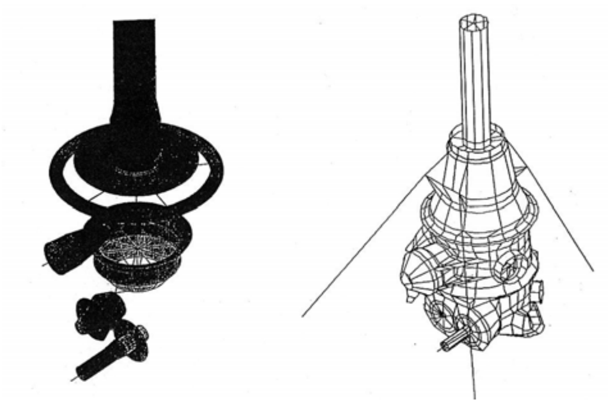
SPIRO to simulate the contact patterns under load, and to define the optimum adjustments.
Although the design time for realizing the ASSYM model (4 months) and for simulating the contact patterns by SPIRO (2 months) was long, this method produced a result within 80% of the optimized solution. The method then converged rapidly on an optimum solution for the contact patterns during the development tests:

- 2 runs on the test bench , and two teeth adjustments proved necessary,
- test duration: 2 months, compared to 9 months for the Super Puma MKI.

***In 1995, Development of the EC120 MGB***

The same method was applied in the development of the EC120 MGB. Thanks to more powerful computers, the geometric models were refined in comparison with the Tiger MGB models. But the same principle was applied:

- modeling the structural components using plate elements,
- modeling the bearings by means of springs.



On the strength of the experience gained with the Tiger, the gearing modeling and simulation times were halved compared to the Tiger. In addition, the result was also very satisfactory since no adjustment was needed for development.
However, the developed, but not optimum, contact patterns were 'touched up' for series production.

For the first time, a spiral bevel gear has recently been developed virtually for the EC120.
The need was then to continue developing the simulation tools, and to refine the virtual development method.

## 4 – THE EC225/725 MGB, A NEW STEP FORWARD IN TOOTH DEVELOPMENT

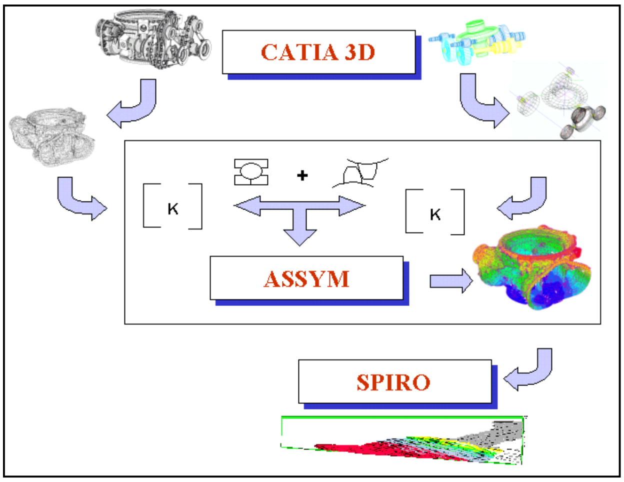
### 4.1 Method

The development process on the EC225/725 was much more difficult than on the EC120 for several reasons:

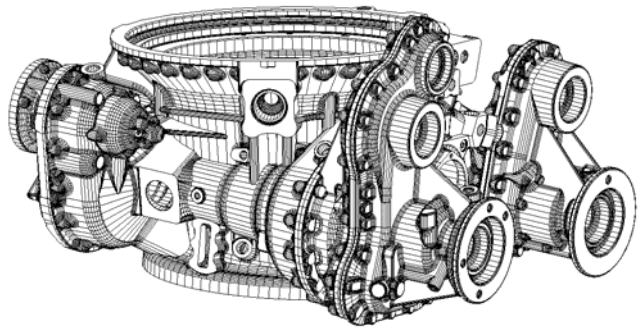
- there were more casings and they had a more complex shape
- the drive train was complex
- a tooth surface had to be defined without changing the basic gearing parameters, in order not to change the environment, especially the bearing assembly.
- the sensitivity to deformation was much higher because of the higher torques (the torque is 10 times the torque transmitted on the EC120 MGB output).

The same approach was adopted as in the previous development processes but enhanced versions of SPIRO and ASSYM were used:

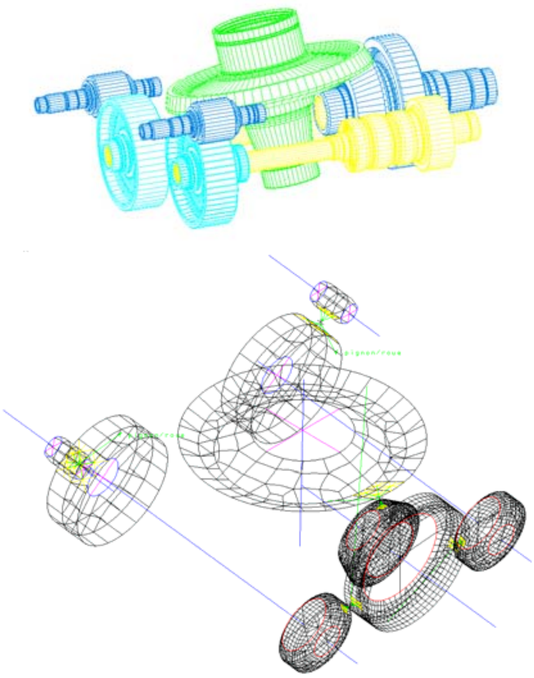
- simulation of the quasi-static behavior of the MGB, and computation of the relative displacement of the pinions at the contacts (gears, bearing)
- at the same time, simulation of the gearing under load, including the deformations calculated previously.
- virtual optimization of the tooth surface, and determination of the machine parameters.
- validation test.



Thanks to the advances integrated in ASSYM and in design software, such as CATIA® , it is now possible in this new step to design and model all the parts in 3 dimensions, regardless of their complexity.



*Casing modeling*



*Drive train modeling*

The drive train complete with its pinions and gearwheels formed the first geometrical super-model. All the casings formed the second super-model.
After being condensed into stiffness matrices, all these super-models were assembled together to form the overall model. The following types of linking elements were used:

- "gear contact" elements: direction, stiffness
- "bearing" elements representing the internal geometry: number of rotating bodies, play, radius of curvature, local contact stiffness, etc.

This super-model assembly formed the global model.

### 4.2 Simulation results

The displacements with torque applied have been computed in order to determine the position errors of the pinions. Two computing cases were run:

- with the power of the 332 MKII MGB (2400 kW)
- with the power of the EC225/725 MGB (2600KW)

Because of the torque being transmitted, the displacements were particularly large on this MGB, highlighting the need of tooth development:

- casing deformation of more than 3 mm
- displacement of 1 mm of the spiral bevel gear cone centers
- axial displacements of 0.5-1 mm of the pinion and gearwheel
- a hypoid (non-parallel) offset of about 0.5 mm on the teeth

Such deformations will obviously have an effect on the meshing surfaces. Thus without any adjustments of the surfaces, the load transmission would generate local overpressures that, in turn, would immediately cause damage such as flaking and scratching.

### *Simulation of Gears under Load: SPIRO*

- Step 1: Validation of the overall model based on the simulation of the 332MKII contact patterns.
This step consisted primarily in simulating the tooth contact pattern under load of the 332MKII spiral bevel gear, by integrating the position errors computed by ASSYM. The pattern was then compared with the patterns generally seen in the acceptance tests of production MGBs. The aim was to validate the overall model by demonstrating that the two patterns - simulated and observed - were very similar.

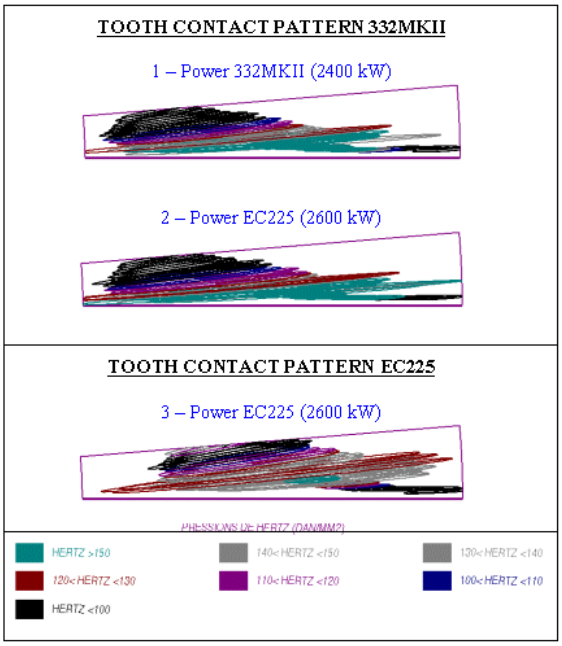
- Step 2: Simulation of the 332MKII teeth at the EC225/725 power (2600 kW).
The purpose of this step was to confirm that the 332MKII teeth could not withstand the power of the EC225/725, and that the resulting Hertzian pressures exceeded the design criterion. There would then be a risk that

defects like those experienced in the past would occur.

- Step 3: Definition of tooth adjustments to optimize the tooth surface at the EC225/725 power.

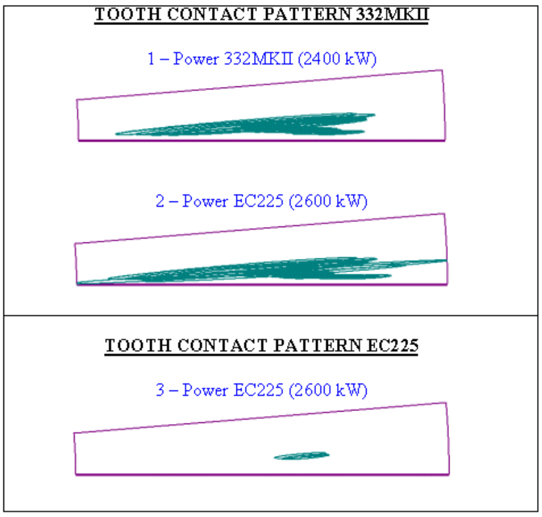
In fact, this is the typical process of virtual tooth contact pattern development, i.e. based on simulation of the gears under load, several adjustments are simulated until an optimized contact pattern is obtained.

- Step 4: Determination of the grinding machine parameters that will produce the optimized contact pattern.




Once determined, these parameters will accurately produce the simulated tooth surface.

*Tooth contact pattern under load*




*Hertzian pressure > criteria*

An analysis of the above plots indicates:

- the 332MKII contact pattern is not today optimum. For instance, there is a relatively large area where the contact pressure is equal to or greater than the criterion.
- The pattern deteriorates significantly when the power is increased from 2400 to 2600 kW. In operation, the pressures generated would rapidly cause damage, such as flaking and scratching.
- In contrast, the new EC225 contact pattern is fully optimized. Within the same space and despite the higher power, the contact pressure is much lower and better distributed.

The last step is the experimental validation of the virtual development result.

## 4.3 Test Results

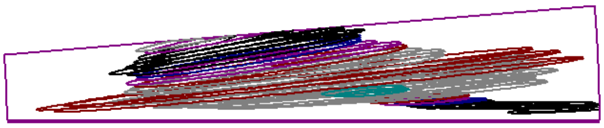
The validation test is made with the MGB back to back on the rotary bench with torque applied. For the test, the meshing surfaces are first coated with varnish. The power is then increased progressively, and the tooth contact patterns examined.

The first EC225/725 MGB was therefore installed on the bench for this test:

- Application of the initial power, equal to 50% of the maximum power. Solely a borescope inspection was conducted to check for satisfactory condition.
- Application of the second power level of about 2000 kW, equal to 75% of the maximum power. The examination revealed a well spread-out contact pattern, complying with the simulated pattern.
- Application of the final power level of 2600 kW, equal to 100% of the maximum power. The examination revealed an excellent and well distributed contact pattern, complying with the simulation.

100% Max power (photo P.MARET)

75% Max power (photo P.MARET)



100% Max power

***Comparison of Simulated/Tested Contact Pattern***

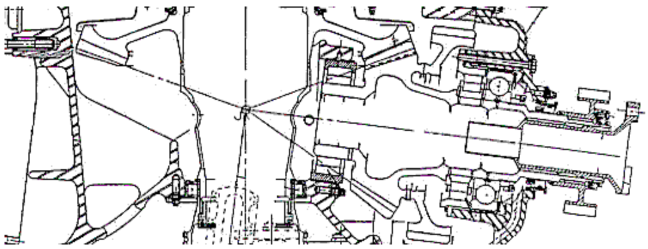
Conclusions

- No adjustments were needed, which is particularly surprising in view of the large deformations.
- For a similar tooth surface on the 332MKII and EC225/725, it was not only possible to transmit a higher load, but also to substantially decrease the Hertzian pressure, i.e. to enhance the tooth reliability.
- The tooth development test only consisted of one validation test of the contact pattern, i.e. three one-hour rotations.
- The development of the EC225/725 MGB spiral bevel gear teeth marked a new advance in virtual tooth development through the control of the overall process.

## 5 – ASSESSMENT AND OUTLOOK

Since the EC225/725 program had a very tight schedule, it was decided right from the start of the project to apply the virtual tooth development method - even though this case, as we indicated above, would in principle be difficult.
In view of this situation and on the strength of the experience on the EC120 and Tiger, it was assumed that one tooth adjustment would be necessary. The resulting development cycle involved 4 months of testing:

- a first run on the bench lasting 4 days (MGB assembly, test, disassembly)
- definition of a single adjustment, updating of the model: 4 days
- manufacture of a pinion incorporating the tooth adjustment: This required 90 days: long because the teeth could not be ground on the finished part. To allow for the displacement of the grinding wheel, the pinion toe had to be added on by electron-beam welding, as shown in the diagram.
- a second run on the bench, and validation of the adjustment: 4 days



***EC225/725 MGB Spiral Bevel Gear***

The virtual development of the EC225/725 MGB resulted in a single run on the bench, i.e. three one-hour rotations: 4 days with MGB assembly and disassembly.

This success saved 4 months in the cycle compared to the MGB development schedule. In addition, once the production definition of the teeth was the same as the definition determined by virtual development, the initial manufactured parts were 'certified for production':

- Shorter manufacturing cycle and fewer parts
- Smaller flight program for the prototype and pre-production aircraft, since the

MGBs for the pre-production aircraft were already fitted with the parts.

- No power limitation for flight testing, which also streamlines the development cycle, or at least simplifies the flight test programs.

In contrast, the major part of the virtual development of the teeth, and the related problems, are dealt with beforehand. The success of this operation requires the following:

- 3D drawings of the casings, which have extremely complex shapes.

- It must be possible, using these 3-D models, to set up the mesh for creating the finite element model. Converting the 3-D model into a mesh is still difficult, because the automatic 'meshers' are not yet effective for large, geometrically complex models. It is consequently necessary "to rework" the 3D model of the design in order to be able to generate a satisfactory mesh. This process is time-consuming and not fully mastered.

- Building the final model is still a sensitive operation, even though very considerable progress has been made since the last development programs.

- Gear simulation and tooth optimization are now fully mastered and quick to perform.

Overall this virtual tooth development took six months, from the construction of the 3D models up to the determination of the adjustments required on the teeth.

The overall process is now mastered, and produces accurate results. But improvements must still be made in establishing the mesh and in forming the final file.

## 6 – CONCLUSIONS

In this paper, the benefits of the virtual MGB concept have been demonstrated by comparing its application in the development of the EC225/725 MGB with past development work on other MGBs. This virtual development has improved performance, lessened the risks, and shortened the cycles.

The EC225/725 MGB marks a new advance in virtual tooth development through control of the overall process.

However efforts must still be made to facilitate, and make more automatic, the upstream modeling tasks and the meshing of complex parts, such as casings.

The virtual MGB concept is not, however, restricted to the sole development of spiral bevel, cylindrical and helical teeth. The same approach is applied for optimizing the internal geometry of bearings, splines, etc. Work is underway to integrate thermal, lubrication and vibration aspects into the virtual MGB concept. The long-term capabilities of the virtual MGB concept will include:

- Provision of a full understanding of the overall operation of the MGB very early on in its design cycle.
- Determination of the manufacturing parameters integrally with the design.
- Acting as a powerful investigating tool for in-service incidents.