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OPTIMIZATION OF AN INTERMEDIATE GEAR BOX

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1 Introduction

ZF Friedrichshafen AG manufactures aircraft products to satisfy market trends. Some of ZF's major partners include: Airbus Industrie, Dowty Rotol, Eurocopter, Fiat Aviazione, Garrett GAPD, LAT.
ZF's business activities, the registered office of the group and the central research and development departments are all located in Friedrichshafen.

2 The problem and the way ahead

During a pre-test of a helicopter intermediate gear box (IGB), performed on an improperly configured test rig, a crack was detected between the body and one of the four legs of the output housing. To prevent any impact on qualification for the first flight, immediate investigative action was taken to localise the cause of failure and, in parallel, to improve the design to significantly reduce any further risk of strength or fatigue failure during IGB qualification.

Strain gauges were installed on a complete housing in the area where the first gearbox had cracked. This was done to evaluate the local stress levels during different operating conditions during the endurance test procedure, for example, during start-up and power variations.

A layer of photo-elastic material was also applied to the area that had cracked as well as other areas of interest to obtain an overview of stress distribution during static load conditions.

A finite element model of the complete gear box should produce two results:
1. Discovery of other stress critical zones of the housing
2. Verification of design changes well before testing

3 The finite element model (Figure 1)

Using experience gained with other FE-models of housings, we know that more reliable results are obtained using a complete gearbox model, including housings, shafts, gears and bearings. In the case of the IGB, the additional effort was minimal; the addition of two shafts with bevel gears, on the input shaft one grooved ball bearing for axial support and two roller bearings for the radial support, a grooved ball bearing for combined support and a roller bearing for radial support on the output shaft.

The housing consists of two main parts, the input housing and the output housing bolted together at a flange. The crack started close to the point at which a leg connects the output housing to the support and the flange, so a coarse model of the input housing had to represent at least adequate stiffness in this area.

As both the failed and the improved output housing design had to be investigated for comparison, relative reduction of stress instead of absolute levels could be used as criteria for the optimization. Shell elements have been found appropriate for the task as they provide sufficient quality for comparison of stress levels, and design changes are easier to model compared to solid elements.

The two parts of the housing connected by bolts were represented using rods to provide the load distribution on the flange.

The bearings are modelled using gap elements in either axial or radial direction, circular between shafts and housing. Thus, a realistic load distribution of bearing forces acting on the housing was achieved.

The shafts and the input and output flanges are modelled with solid elements. The bevel gears are represented by solid cones with adapted stiffness for teeth. For the actual problem it was sufficient, to transmit the torque and force from input to the output through a single point of contact in a direction normal to the tooth flank.

In order to achieve the correct stiffness for the housings, the aluminum covers were added by a coarse mesh of shell elements.

The structure is fixed to the ground at the four legs.

The input torque is applied by three tangential forces at the input flange, and it is reacted by three tangential restraints at the output flange.

4 Results of the FE-model

Output housing

The maximum principal stress in the area of the crack was 86 MPa.

The overall maximum stress appeared near the flange between input and the output housing with 149.5 MPa, so another stress critical area was detected, and became subject to photoelastic coating.

A costly and time consuming overall coating could be avoided because the interesting zones were known from the FE-analysis.

Input housing
One of the stiffeners of the input housing showed a stress level of 93 MPa which was not seen as really critical, but subject of improvement before next purchase.

Other items of interest as load distributions on bolts were used to check these parts:
There is a maldistribution factor of 1.35 on the three bolts of the output flange.
The 12 bolts of the flange between input and output housing show a maldistribution of 3.1.

5 Results of investigations

Strain gauge measurement showed a stress level of 86 MPa at the specified maximum static load. Under equivalent dynamic loading the same mean stress appeared but with a superimposed sinusoidal dynamic stress with an amplitude of 45 MPa. So stress alternated between +41 MPa and +131 MPa.

The dynamic stress and amplitude were unacceptable for the used material, a magnesium casting.

The evaluation of static stress level by coating with photoelastic material indicated a 50% higher stress level near the strain gauge rosette at a stress raiser where strain gauges could not be applied.

A reduction of the max static stress level by 50% would solve the problem anyway.

6 Improved design

The deformation of the output housing showed, where the structure was not stiff enough and transition to stiffer parts caused stress concentration.

On bottom left of figure 2 the deformed structure shows a stretching of the stiffener between the two legs and the total leg is bent out. In other views it could be seen, that the plane area in the centre of the picture (oil sump) is sinusoidal deflected from left to right,so it bends to the inside in the right and to the outside at the left. Increasing the wall thickness of the plate and increasing the basis of the legs, additionally improving the section of the stiffener between the two legs reduced the maximum stress by 52%. Stress investigation on the improved housing by photoelastic coating showed even 68% reduction. The difference is explained by the local improvements, say smoothening of the transition from leg to body of the output housing, which could not be modelled with the shell elements.

Figure 3 shows on the left side of the output housing the bent shape of the flange. The area where the flange was connected to the housing was increased and the flange was better supported by a smooth conical transition to the body of the output housing. This stiffer flange increased the force on the maximum loaded bolt by less than 5%, but the stresses on the housing were reduced by 35%. Comparison of stresses on top and bottom of the shell elements showed, that the bending was replaced by tension. Photoelastic coating of the output housing established a stress level of 48% of the FE-stress, the reduction on the improved design was 46%. The explanation for the deviations is, that the local geometry could not be modelled with shell elements and besides the global improvements in stiffness, the increased local radius caused an additional stress reduction.

The necessary pattern change gave also a chance for general stress related improvements:
Together with the pattern maker stress raisers were smoothened. Connection of the legs to the cylindrical part of the housing and the stiffeners between the legs were strengthened.

6 Résumé

Housings of gear boxes are usually castings, this means new or modified parts are always long lead time items. Due to the complex geometry stress distribution and distortion under load cannot be evaluated by classical analysis. The short development times for new products do not allow to develop and optimize a gear box by loops of several prototypes and tests. For suppliers of components the situation is worse due to late vendor selections and even later contractual agreement. Retrofit actions caused by insufficient strength or fatigue strength are extremely expensive, but until full fatigue qualification a lot of gear boxes are already in service. This all is valid for gear boxes in all applications, so our management decided years ago to have research and development programs to predict static and dynamic behaviour of gearboxes and in parallel to have equipment and specialists to prove the methods by comparison to test. The methods are now well established and mostly used in the early design phase. FE-modelling, -calculation end -postprocessing has become so quick, that in well planned new developments the gear box housing is optimized before the pattern maker starts his work.

Using these tools, expensive development test and prototype loops in hardware are avoided.

Please remember:
The objective of the qualification test is to demonstrate, that the gear box fulfils specification and not to discover the deviations to that.

Figure 1

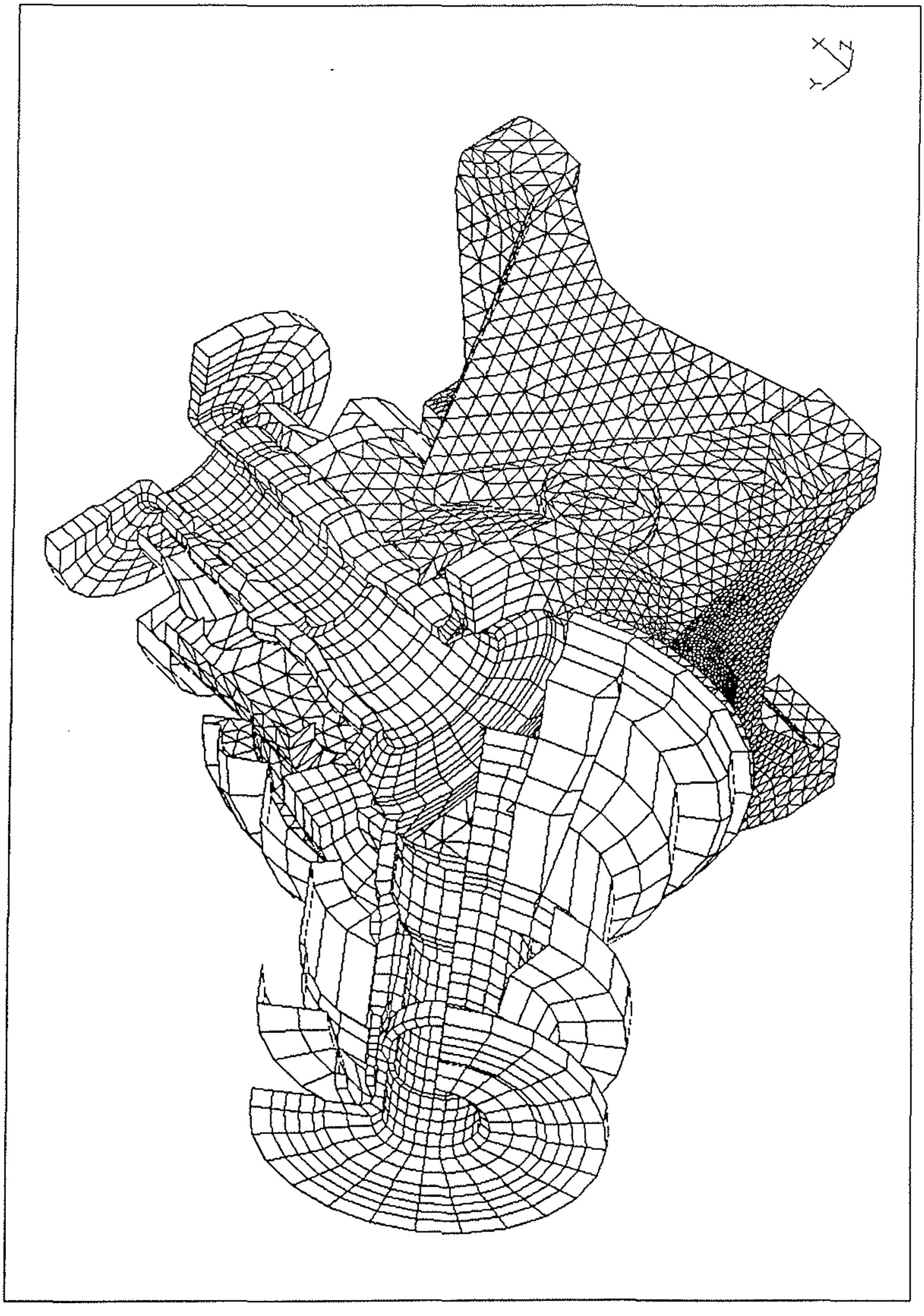

Figure 2

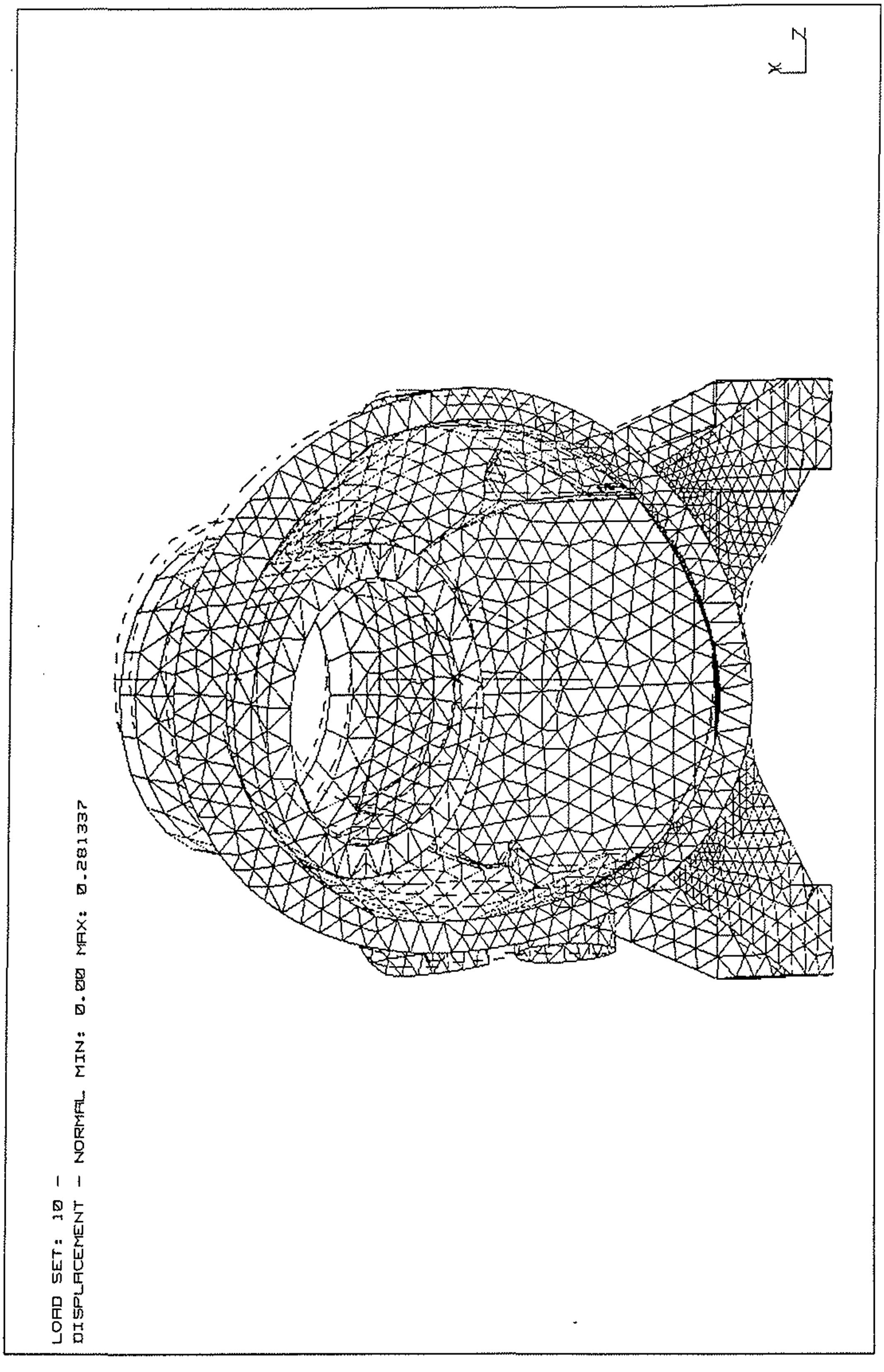

Figure 3