X-38 HOT RUDDER MECHANISMS

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ABSTRACT

One of the significant challenges in the realisation of the manned International Space Station is the development of a Crew Return Vehicle (CRV). This vehicle would serve as both an ambulance for medical emergencies and as an evacuation vehicle for astronauts/cosmonauts in case of calamities on the ISS.
The CRV technology development is in its early stage as part of a NASA technology demonstrator program, called X-38.
ESA has offered to develop parts for the X-38 demonstrator as technological precursor of CRV. As such The Netherlands are involved in developing the rudder for the X-38.
The Dutch participation consists of a number of industries and institutes called the AEOLUS-team. Fokker Space and Stork Product Engineering are the leading industries, with TNO Prins Maurits Laboratory, NLR (National Aerospace Laboratory) and DUT (Delft University of Technology) as its strategic partners.

As for all control surface systems of this vehicle also the rudder has to operate in an extreme thermal-mechanical environment. During re-entry high temperatures and high thermal gradients are generated in combination with high mechanical loads (inertia- and aerodynamic forces).
While for the major part of the X-38 vehicle a classic Space Shuttle like thermal protection system is chosen, (i.e. ceramic tiles), the control surfaces will be preferably unprotected, i.e. a reusable hot structure.
This paper addresses the design and analyses of the mechanisms in the rudder (floating skin, hinges).

INTRODUCTION

The design of the hot rudder and consequently its mechanisms are based on the following conditions and design goals (see fig.1):

- the high temperature generated during re-entry.
- the use of a hot structure based on metal.
- the dilatations and deformations of the rudder should not result in extra loads in the hinge-supports of the rudder and the connections to the structure of the vehicle (statically determinate support).

In this paper the emphasis will be laid on the following aspects:

- the thermal and mechanical loads as induced by the hypersonic aerodynamics during re-entry (design driving requirement).
- the overall rudder structure (hot structure).
- the interconnection of rudder skin to rudder internal structure and the problems experienced with the design of the “floating skin” structure.
- the support of the rudder by a gearbox and bearing hinge-system, including the design features to make them functional under the thermal-mechanical loads on the rudder and the distortion of the rudder.
- a short review of the results of the combined thermal-mechanical and kinematic tests on the rudder

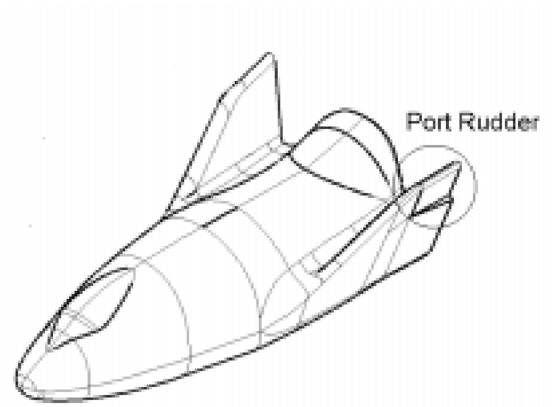

fig.1. X 38 vehicle

AEROTHERMODYNAMICS OF RE-ENTRY

The nature of an atmospheric flight from a low earth orbit differs in many respects with present aircraft, even in supersonic flight. The initial re-entry velocity is nearly 8 km/sec and at such hypersonic speed the flow field is dominated by the extremely high temperature of the atmospheric gas that is heated by a very strong shock wave. Behind the bow shock the temperature raises to about 10000 K causing dissociation of oxygen and nitrogen molecules. This is an endothermic process and

the temperature consequently decreases to about 6000 K shortly behind the bow shock. The chemical composition along a streamline is not constant any more and heat transport is associated with dissociation of molecules and recombination of atoms.
The outer skin of a re-entry vehicle is heated in two ways. The friction in the boundary layer caused by very high velocity gradients leads to a high boundary layer gas temperature and a high heat transport to the skin of the vehicle. The second way is the recombination of oxygen and nitrogen at the skin where the skin material acts as a catalyst. This part of the thermal flux depends on the catalycity of the skin surface. Bare metals are highly catalytic, ceramics are very low catalytic. The results of the aerothermodynamic calculations with respect to the skin temperatures versus time are depicted in fig.2. The re-entry starts at an altitude of 120 km.

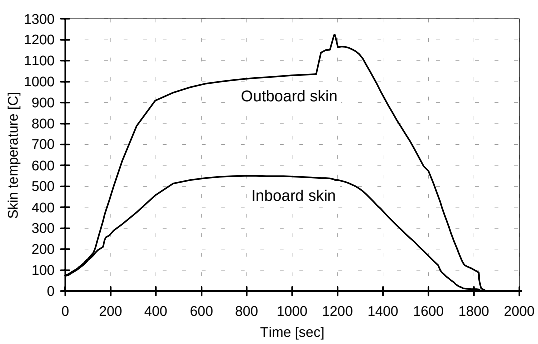

fig.2 Skin temperature during re-entry.

MATERIAL SELECTION

Selection of the outer skin material shall be done very carefully. The lessons learned from the US Space Shuttle are that the maintenance costs should be kept as low as possible when reusability is required. Strength and stiffness at elevated temperatures shall be sufficiently high but also protection against the very hot aggressive oxygen in the boundary layer is an important consideration. The temperature of the skin is determined by the balance of heat input by the hypersonic flow, the heat output by radiation and heat flow into the internal structure.
This means that the emission coefficient has a direct impact on the skin temperature, leading to the requirement of a high total emission coefficient of the skin. Most materials and particularly bare metals have a low emissivity so that a coating is needed that is not only low catalytic, but also self healing against damage and resistant to high temperatures and temperature gradients. It may seem that only the notorious material "unobtainium" is able to meet these requirements but surprisingly enough several materials are available that meet these requirements, like some ceramic composites and ODS (Oxidation Dispersion Strengthened) alloys. However all materials have specific advantages and disadvantages. The rudder team has selected the Nickel based ODS alloy PM 1000 produced by the Austrian company Plansee. This alloy has a good strength and stiffness up to 1250 °C (fig. 2) but moreover the alloy naturally develops a dense protective oxide layer of Cr_2O_3 at high temperatures that protects the material against hot oxygen and this oxide layer also has a high emission coefficient ranging from 0.8 to 0.9.
Extensive testing of the oxide layer by radiation heating revealed the excellent self healing property and the stability under high thermal gradients. Beside these valuable properties the material costs of this alloy are much lower compared to ceramic composites.

HOT STRUCTURE

The design goal of the X-38 rudder team was the development of a reusable metallic "hot structure" without an external thermal protection system. The term "hot structure" not only indicates that the outer skin will reach a high temperature but also that the load carrying structure itself is hot. The objective is to obtain a design with a lower structural mass than the conventional solution with a cold load carrying structure (mostly aluminium alloy) and thermal protection tiles overhead.
During the design phase the inherent disadvantage of metals became manifest: the high thermal expansion coefficient compared to ceramic composites and the steep thermal gradients inside the material caused very high stresses. Extensive thermal-structural analyses proved that the height of a continuous stiffener on the skin, to be used for strengthening and attachment to internal structural parts, has to be limited to 11 mm to avoid fatal thermal stresses.
This problem not only occurs at the stiffeners, but also at the trailing edges between the side skins and the rear skin and at the two bottom edges. The rear skin and the bottom skin are heated much less than the side skins and especially the outboard skin and this causes thermal stresses in the same way.
This made the rudder team conclude that a classic integral box structure using flat skins and sharp edges at the corners is not feasible.
A solution to pass this obstruction is found in a sliding connection of the skin plates at the critical edges in stead of a rigid connection. The capacity of the skin as load carrying part, however, is reduced considerably by this. To compensate for this a stiff and strong truss structure has been applied inside the rudder. This truss frame, to be called rudder frame, is connected to the brackets for the gearbox and the bearing. The skin panels are connected to this rudder frame by means of struts with hinged ends and directed perpendicular to the skin surface, to allow for free expansion, (floating skin) see fig.3 and fig.4. The load carrying task of the skin panels is reduced to take the pressure difference across

the skin and to transfer it through the struts to the rudder frame.

Two options are considered for this frame, a non-insulated PM1000 frame and a frame insulated by a lightweight thermal blanket around it and made of the titanium alloy annealed Ti-6Al-4V. The special designed and tested insulation (type REFREX, supplied by the Dutch company Insulcon), reduces the frame temperature to 400 to 500 °C, suitable for this titanium alloy.

Thanks to the excellent properties of this titanium the mass of a frame made of this material together with the mass of the thermal blanket is lower than that of the PM1000 alternative. Therefore the titanium option is chosen.

The benefit of the thermal protection is not only the lower temperature, but it also the improved temperature distribution over the rudder frame. This reduces the thermal deformation of the rudder, compared with the values predicted for the self supporting skin.

The temperature difference between the rudder frame and the skin, and the difference of the coefficient of thermal expansion of the frame material compared to that of the skin material results in a considerable mutual displacements (in X-Y plane) of the skin and frame. To allow this displacement, the connection of the floating skin panels to the rudder frame has to be statically determinate. This is realised by adding two more connections for in plane support to the already mentioned out of plane support by the struts. One connection of the two is for support in two directions, X and Z and the other one for support in only the X direction. In fig.4 these supports are drawn at the upper left attachment point for the struts (for X direction only) and at the upper right one (for X and Z direction). These lateral displacements are proportional with the distance from the X,Z support and amounts to 6.5 mm. for the farthest strut, corresponding with 4° obliquity. The rotation of the ends of the struts due to this displacement is minimised by making them as long as possible but nevertheless analysis proved the necessity to apply spherical joints at both ends of each struts, as drawn in fig. 4 and 4a .

The number of struts required depends on the capacity of the skin to withstand the pressure difference across the rudder. To increase this load capacity in order to minimise the number of struts as much as possible, stiffeners are made on the inner side of the skins. However the effect of this is limited by the limitation of the height of these stiffeners to the earlier mentioned limit of 11 mm.

The spherical bearings are heated up to the skin temperature, so, they are hot mechanisms pre-eminently for which the following requirements are applicable:

- operational temperature maximal 1200 °C.
- should be compact, to save mass, not only important for the overall rudder mass, but also important to avoid accumulation of mass at the skin which increases the thermal stresses.
- enable easy assembly due to the difficult accessibility of most of the attachment points.
- no or very little backlash allowed to ensure a firm connection of the skin , during launch as well as during re-entry.
- the bearing should be durable, to survive a multitude of re-entries.

In fig. 4 the spherical joint is drawn as a part of the the skin, and in fig. 4a in more detail.

It consists of a specially shaped shaft with cylindrical ends and a sphere in between with two flattened sides.

The purpose of this special shape is that the spherical part of the shaft can pass in just one position through the special cut out in the spherical hole of the strut. In the operational position the spherical shapes fit together, but to achieve this fit the shaft has to be rotated 90°. In this position the shaft is locked.

As the temperature of the strut end is almost equal to the temperature of the skin, the application of the same material as for the skin is evident, i.e. PM1000.

As mentioned before one of the properties of PM1000 is the formation of a dense and self healing oxide layer. These oxide layer is also very hard and this prevents fretting of the moving parts, presuming that the oxide layers are strong enough to carry the contact pressure. For this reason the contact pressure is kept moderate at maximal 60 N/mm^2 . The check whether this oxide layer is strong enough has been part of the tests on the rudder. To be sure that a proper oxide layer is already present at the start of the test the parts of this spherical bearing have been pre-oxidised.

CONNECTION OF THE RUDDER TO THE FIN STRUCTURE

Two starting points had large impact on the design of the support of the rudder on the fin structure:

- the results of an extensive thermo-mechanical analysis on a preliminary design of a rudder with a self supporting skin structure.
- the choice of the gearbox by NASA for the electro-mechanical drive system, i.e. a compact double slice gearbox as used in the F16 fighter.

The analysis gave the temperature rise during re-entry of various parts of the rudder, in particular the skins, the internal structure, the brackets for bearing and gearbox.

The temperature of the gearbox and bearings would not exceed 400 °C, a temperature that a mechanism can withstand for a short period of time if it is well prepared for this condition.

This analysis also indicated a “banana” shaped deflection of the rudder due to the temperature difference between the skins indicated in fig.2, especially between the outboard and the inboard skin. At

the front spar, near the hinge line of the rudder, the out of plane displacement (Y-direction) was predicted at 4 mm and the elongation of the rudder w.r.t. the fin at 10 mm (Z-direction).
The magnitude of this deformation is such that it was decided to make the support of the rudder statically determinate. This means that the rudder has to be supported by just two hinge points. One of them should be the gearbox, while for the other hinge point a bearing is required.
The gearbox is already internally provided with bearings for axial and radial support. This makes it the most suitable of the two to provide the axial support (in Z- direction), see fig. 3 and 5. To reduce the variation of the gap between rudder and fin during the temperature rise of the re-entry, the axial support, the gearbox, should be located as low as possible.
This is also an advantage for the simplicity of the drive.
The upper hinge, the bearing, is located high, at the height of the pressure point of the rudder. As a result the bearing will support almost the whole force. introduced by the pressure difference across the rudder. This is the major force in Y-direction. The benefit of this configuration is that the gearbox is relieved as much as possible from supporting loads. It only has to support half of the loads in X-direction and the full axial load in Z-direction.
To prevent a conflict between the axial support of the gearbox and the upper hinge, the upper hinge should allow some axial displacement.

brackets for the gearbox.

The gearbox has a relative small diameter compared with the available width inside the rudder, about half of the width, see fig.5. However , as it is a double sliced one, it means that it is relatively long , with twice as much attachment points as a single slice and that they are spread over a longer distance relative to the length of the fin rudder interface. This makes that the connections of this gearbox to the two sides can be regarded as rigid connection, much more rigid than that of a single slice gearboxes as explained in paragraph *impact of the selected gearbox.*.
Complications in the connection of the rudder with the fin are the previous mentioned dilatations and especially the banana shaped deformation of the rudder. These complication only occurs at the rudder side. At the fin side, which is the cold structure body of the X38, there are no or negligible thermal distortions, and therefore the straightforward connection of the gearbox with fixed brackets to the fin side is chosen. At the rudder side, however, the thermal distortions and the deformations cannot be accommodated by a rigid connection.
Therefore the following statically determinate arrangement is designed, drawn in fig. 3 and 5.
An intermediate bracket is introduced which is rigidly connected with the gearbox by means of 4 pairs of lugs, providing 4 connection points. For the connection of this intermediate bracket to the rudder just two connection points in X-direction are applied, by means of links with spherical journal bearings at the ends.
These spherical bearings ensure that only support in the desired direction occurs, so in X and around Z direction (drive torque) and that there is a freedom to rotate around the X and Y axes.
The distance between the two links is about twice the distance between the lugs, which is favourable for the stiffness and the sensitivity for backlash.
For support in Z and Y direction with freedom to rotate around the X and Y axis, a spherical bearing is located inside the intermediate bracket.
A bracket mounted at the rudder with a shaft at its end fits in the bore of this bearing. It is a sliding fit to prevent any conflict with the already existing support in X-direction. This bearing is not visible in fig.3 and 5.
The intermediate bracket is divided in two parts mutual connected by two hinges, fig.5. This hinge connection, called inter bracket hinge in fig.5, is introduced to allow an expansion of the gearbox, without introducing extra loads on the connections to the gearbox (the lugs). This inter bracket hinge (fig.5 consists of two parts, one at the top side of this bracket and the other at the bottom side. In the space between these hinges the spherical bearing for Y Z support is located, mounted in one of the two intermediate bracket parts.
Analysis has indicated that it is possible to replace this inter bracket hinge by a thin interconnection wall. However, for the demonstration model, to be used for tests, the, in kinematics point of view, more transparent hinge type version is chosen.
The material of the bracket is annealed Ti-6Al-4V, the same material as used for the rudder frame. The similarity of the material is also favourable for compatibility reasons. This material is well suitable for the temperatures for which the brackets are designed, 300° C at the gearbox side and 400° C at the rudder side.

Main bearing and its brackets

The upper hinge bearing brackets have to allow for thermal expansion of the rudder side w.r.t. the fin side (Z-direction).
This is achieved with a fixed bracket at the fin side and a swivelling bracket at the rudder side with a self aligning bearing mounted in it.
At regular temperature, below 100° C, a spherical roller bearing would be the most suitable bearing, but for the hot environment a special ball bearing has been designed by the bearing company ADR on the basis of a double row angular contact bearing in X-configuration, full complement, so without cage and the maximum number of balls. In the X-configuration, with the race

curvature well adapted to the contact angle, 0.2° of misalignment can be accepted without loss of load capacity and without introduction of a serious tilt moment .

The bearings are made of a special heat resistant steel, type, AFNOR X40CrMoVN16.2 **,** while the balls are made of AISI M2.

This material is preferred above ceramic, SiN3, for the balls because of the importance for heat conduction to minimise the temperature differences across the bearing. During launch at low temperature as well as during re-entry a backlash free operation of the bearings is required. This means that preload should be present in these conditions. The difference of the coefficients of thermal expansion of the bearing materials $10.6*10^{-6}$/°C and that of the applied titanium alloy, $9*10^{-6}$/°C is small and analysis showed that preload can be maintained in this temperature range.

The bearing rings are solid lubricated using silver plated on the races of both bearing rings.

For the upper hinge ball bearings are preferred above sliding bearings due to the following considerations:

- large angular travels.
- the maturity of soft metal lubrication in ball bearings.
- the low friction of a rolling element bearing.
- the availability of experience in high temperature applications by the ball bearing manufacturers.
- there is no or very limited experience with sliding bearings at high temperature and large movements.

Impact of selected gearbox

Considering the gearbox brackets as described above, they are based on the selected double slice gearbox. For the hot rudder a single slice gearbox with a larger diameter, to provide the same torque capacity in one single slice , would be much more favourable. The two pairs of lugs at the rudder side would enable direct attachment to the two links to the rudder, making the intermediate bracket superfluous.

In this case a statically determinate support can be realised with a far more simple mechanism.

TESTS ON THE DEMONSTRATOR MODEL

The first version of the hot rudder is the demonstrator model, fig. 6. Its purpose is to be subjected to realistic external and thermal loads in a test set-up to verify the suitability of the design. All the design features as described above are incorporated. Once finished, the D-model design has been analysed thoroughly by a non linear thermal-mechanically FEM-analysis performed with ABAQUS, not only to verify the design, but also to provide a basis for comparison with the test results. The results of the analysis as well as the test results indicated that the two statically determinate supports, one for the skins, the other for the connection of the rudder to the fin are so effective in blocking the heat transfer to the fin that the temperatures of the gearbox and brackets are much lower (about 200 to 220 °C) than expected by the analysis on the preliminary design. The struts for the skin however are still subjected to the skin surface temperature.

The tests on the rudder are performed at DVLR in Germany, in a test installation that provided the possibility to apply simultaneously mechanical loads, during activation of the drive system of the rudder and the application of the same thermal load as during re-entry. The heat flow was generated by a series of high power quartz lamps, covering both skin surfaces, completely, from both sides. The external loads were applied at the ends of the struts.

Fortunately, the rudder has withstood these tests very well, even at 130% of the maximal heatflux and during 11 simulated re-entry cycles without any failure in mechanism and structure. Only a slight deformation on the outboard skin plate, occurred during the first cycle and did not increase during the next thermal cycles. This gave an indication that the fear for high thermal stresses is not overdone.

The test also showed that the prediction of temperatures is reliable, giving confidence in the non linear analysis tools used for the design.

CONCLUSION

- The presented hot rudder design, survived the thermal-mechanical tests successfully, without failure in structure and mechanism, which proves the feasibility of the whole concept as well as the components.
- The temperatures predicted in the final analysis were very close to the measured values, proving the reliability of the thermal-mechanical analysis tools. The thermal insulation performed as predicted.
- The combination of statically determinate support of the skins and thermal insulation of the rudder frame resulted in low temperatures in the gearbox, and the bearing and the brackets and in low thermally induced deformation of the rudder frame. Therefore a more classic bracket design might be used in this case.
- However the design of statically determinate support of the rudder as described will be useful in combination with a self supporting load carrying skin design. The Aeolus team still continues the development of this ideal concept.
- If a statically determinate support is designed for a new control surface, then more attention should be paid to type and optimal outline of the actuator for this support, to avoid complexity as possible.

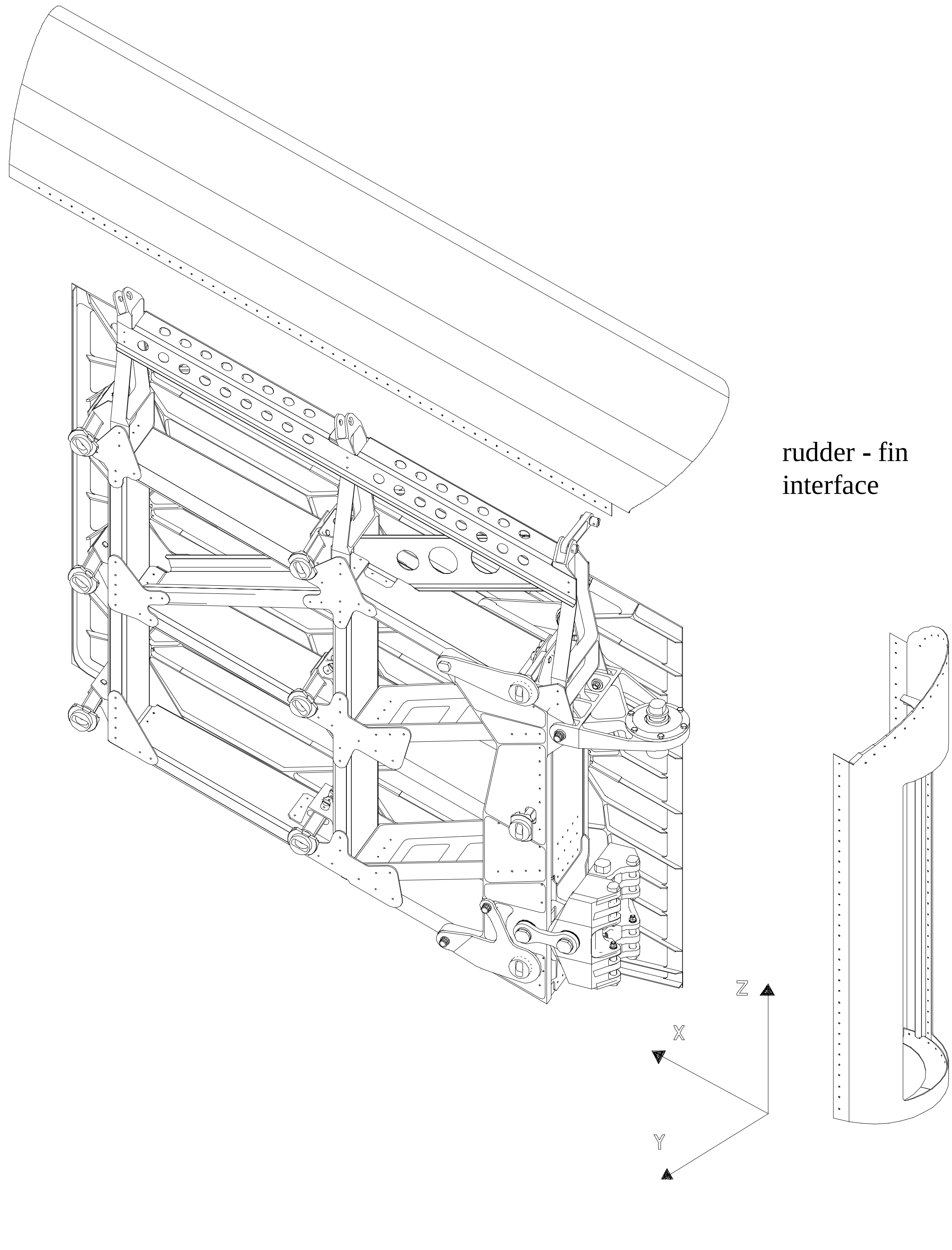

Fig. 3   Rudder frame, exploded view

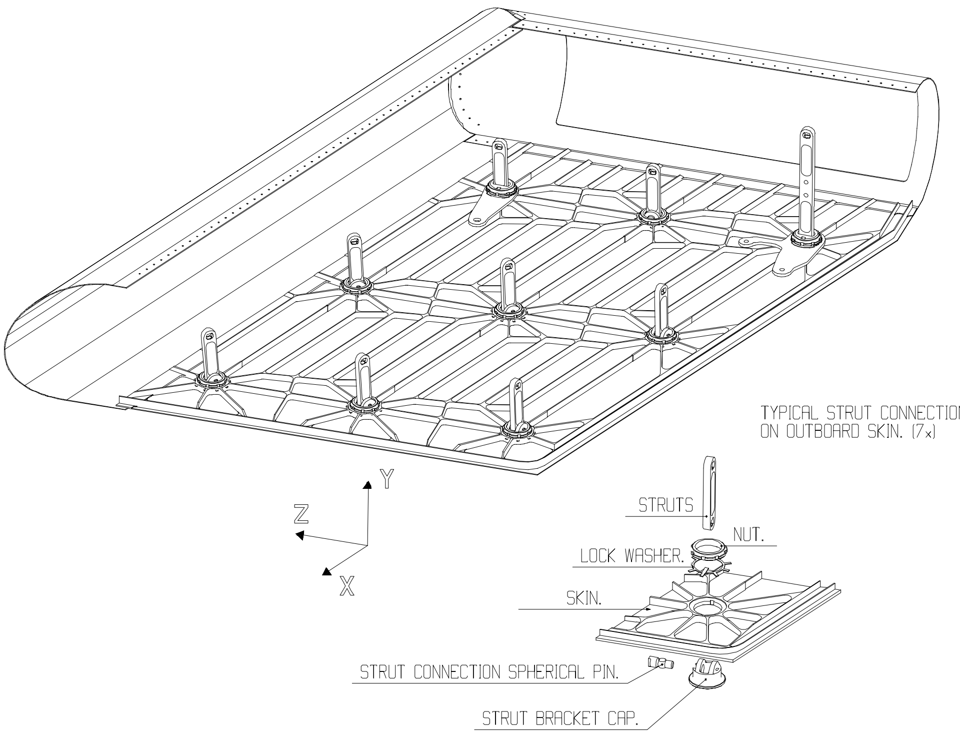

Fig. 4 Skin panel with struts and detail of strut attachment

Fig. 4a Spherical bearing in strut attachment

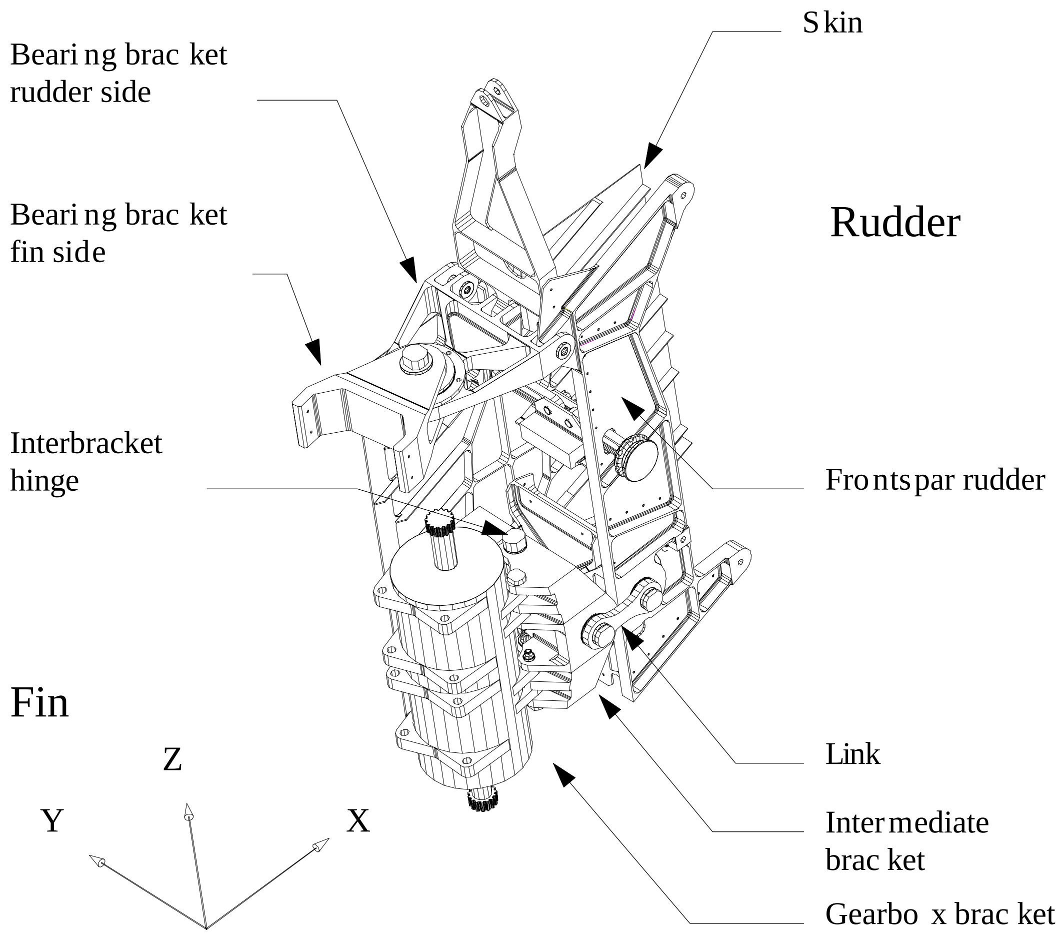

Fig. 5 Rudder hinge brackets

Fig. 6
Rudder, prepared for thermal-, mechanical- and kinematical test at DLR-Germany