Two Examples For Engineering Challenges

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Abstract

As new fellow of the French Air and Space Academy - similar to each new member - I was asked to give a presentation describing my career as engineer. Because I have worked on many programs, I decided to condense my CV into a table(see appendix) and present only two interesting and complex examples out of my experience:

1. *Tornado Wing Pivot*
2. *Bo 108 / EC 135 Bearingless Main Rotor*

Normally wings on aircraft are fixed. But the Tornado was designed as aircraft using *variable wing sweeps*, which in 1970 was and I believe even today still would be challenging. *The task was to introduce hinges to the wings and allow for wing movement during flight(VG[1]).* It was tried to fulfill two contradicting requirements: *high speed, low level attack and STOL[2] operation.*

Again, at least, in the 1950/1960 time frame helicopters used fully articulated rotors. But MBB[3] decided to develop *bearingless rotors.* In this case it was *the task to eliminate the hinges on the rotor blade attachment* to reduce the complexity and improve control response.

[1]Variable geometry
[2]Short take off and landing
[3]Messerschmitt Bölkow Blohm, the main German element of the Airbus Group

1 Tornado Wing Pivot

1.1 Why Swing Wing Aircraft?

The first main requirement for the Tornado Weapon System was all weather, high speed, low level attack. Therefore the aircraft needed an automatic terrain following system and highly swept, relatively small wings(fig.1).

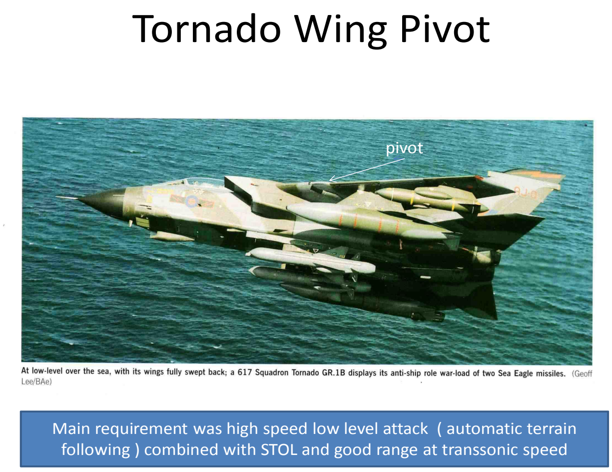

Figure 1: Tornado(high speed configuration)

Fig 2. shows how the gust response/cockpit comfort at high speeds and low flying altitude(Ma 0.5-1.2/ 60ft.) is influenced by leading edge sweep angle. *High sweep angle and high wing loading result in lowest gust response at low level attacks.*

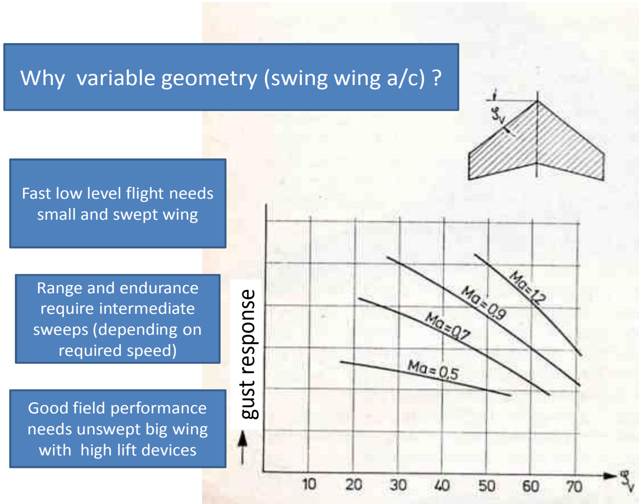

Figure 2: Gust response

*The second main requirement was STOL operation.*For this task big wings with low sweep and sophisticated high lift system would be the optimum choice(fig.3).

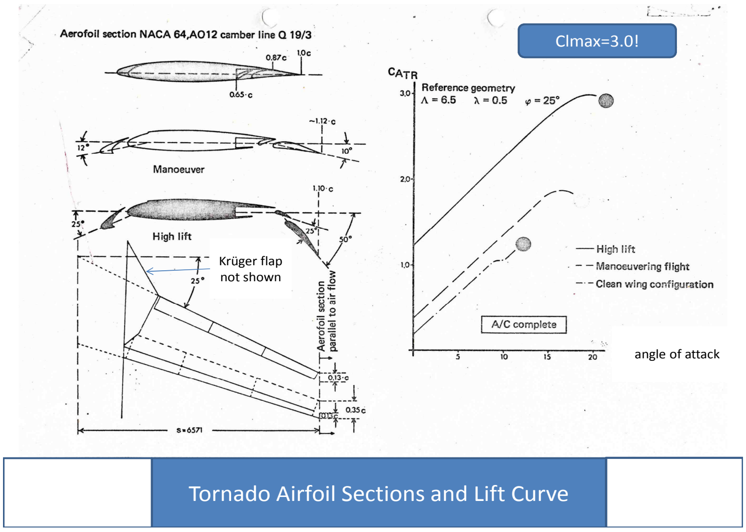

Figure 3: STOL conf.

The VG configuration was considered to be the best overall compromise for these two totally contradictory requirements. Fig4 shows how a VG wing approximates the optimum wing sweeps for different Ma numbers.

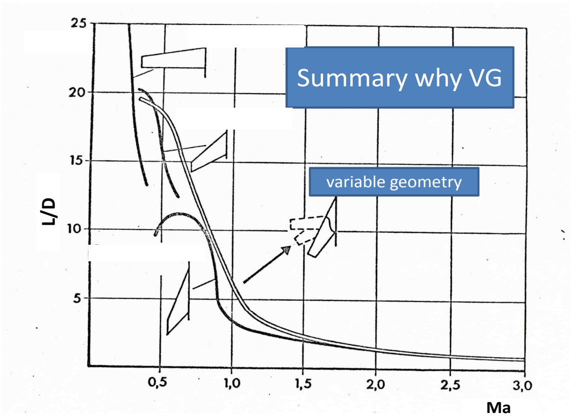

Figure 4: Reason for VG.

1.2 Challenges of Swing Wing Aircraft

But VG aircraft were *unconventional* and we had to tackle many *unknowns and difficulties*:

- There were *"classical" problems* by the tremendous amount of data, because in the case of VG there is at least theoretically an unlimited amount of configurations to be considered:
  - different sweeps(25.....67 degrees)
  - sophisticated high lift system at 25 degrees sweep
  - maneuver flaps and/or slats between 25 and 45 degrees
  - many combinations of external loads/weapons at different and varying wing positions
- *The second class of tasks were "non classical"* and were the consequences of VG:
  - The right position and structural design of the pivot and wing sweep system(see fig.5)

– The sealing between the upper and lower wing surface at the wing root taking wing sweeping and flexibility into account. Very problematic was an aerodynamically smooth fairing, covering the fixed and moving parts of the wing and again mastering changes in contour during sweeping and deflection of the wing(fig.6).

– Impact of wing movement on primary and secondary flight control systems, on fuel lines and synchronization of external load attachments

– unconventional flutter modes .

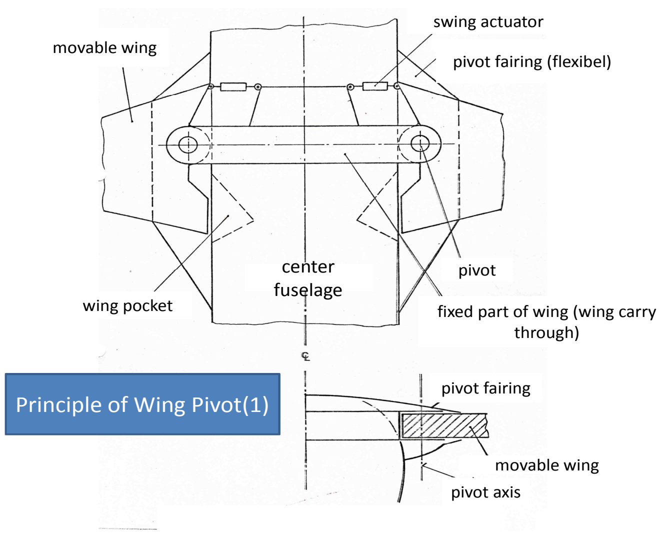

Figure 5: Principle arrangement

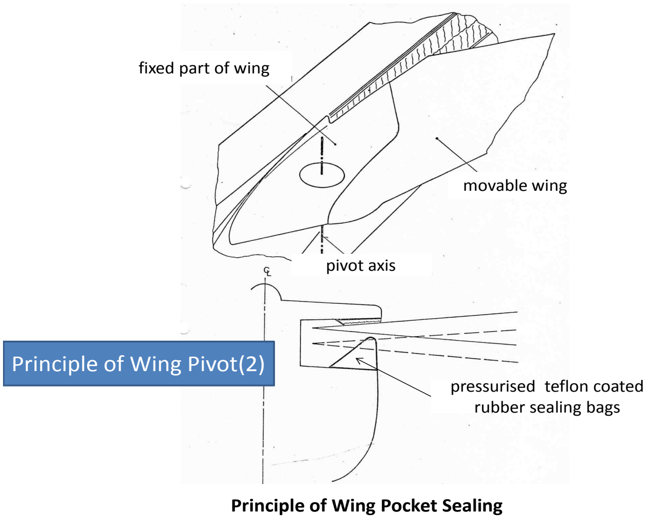

Figure 6: Wing fairing and sealing bags

1.3 Wing Pivot System

As relatively young and inexperienced engineer I was responsible for the design and strength of the German part of the Tornado at that time. Most interesting was the design of the pivot itself. I got all the "advice" you could get at that time in Germany. But unfortunately every "expert" came up with a different proposal and none was supporting our design. Some of them stated publicly that the solution we selected would never work.[4] After very comprehensive testing we selected parallel pivot lugs and an own shear device for vertical forces, allowing some redundancy in the bearing surfaces(fig.7) and Teflon as bearing material. The allowable surface pressures were selected very conservatively(fig.8).

Because this whole arrangement is flexible we had to optimize the stiffness's such that the loads were going as wanted, vertical loads via shear device and forces in direction of the wing plane via the lug bearings trying to avoid direct bending of the lugs. Finding the right relationship of strength and stiffness was not easy. In addition we did not know how the situation changes when the wing was moving because in this case the friction behavior in the bearings changes.

[4]Here I made the important experience that "experts" are never made responsible for their wrong statements, but being wrong doing the job would be very detrimental for you!

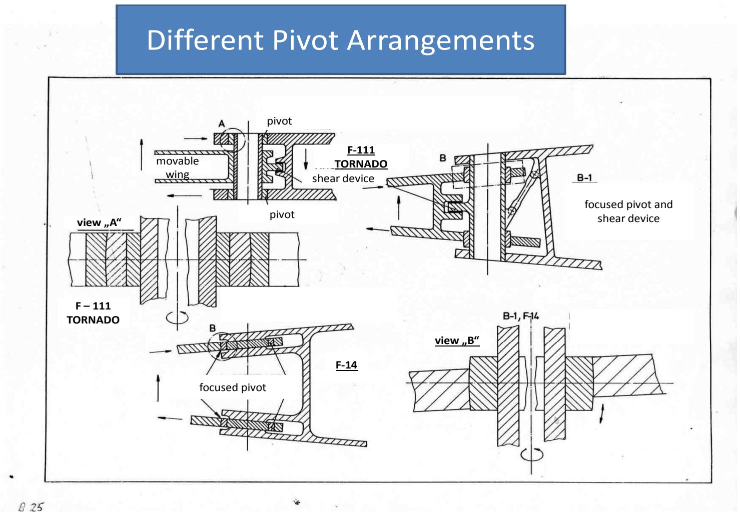

Figure 7: Principle of pivots

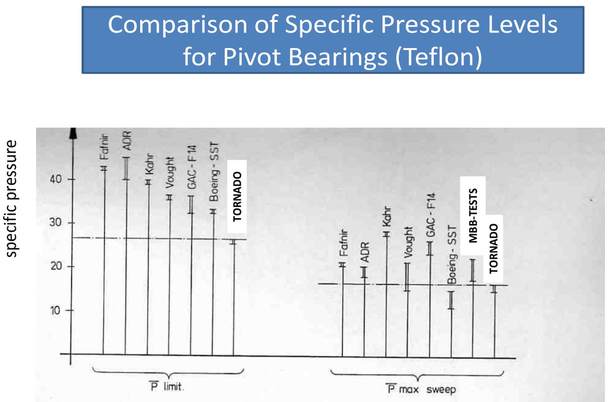

Figure 8: Comparison of bearing pressures

Integrating the central, highly loaded , fixed part of the wing structurally into the fuselage, which was made mainly out of high strength aluminum alloys(7075/7050-T73), was a very difficult task. To allow easier calculation , clear load paths and interchangeability of the box we made a design with several concentrated attachment points(2 points for z and y-forces and 4 for z-forces,2 inboard and 2 outboard longerons for the x-forces).

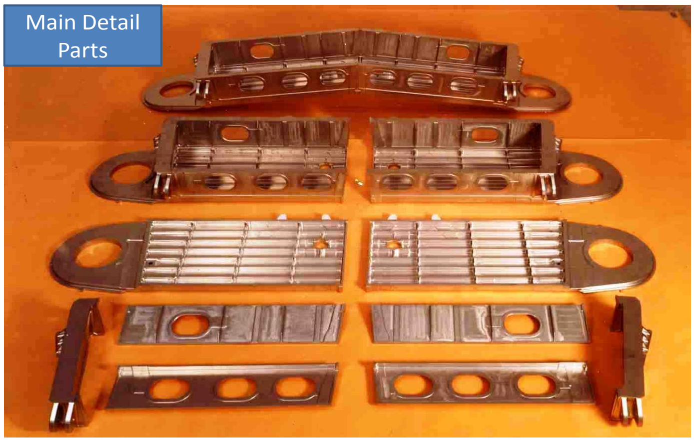

Figure 9: Detail parts of wing carry through box

The extremely loaded box serves in addition as integral fuel tank. The detail parts were made out of Titanium 6-4 in the annealed condition(fig.9) and were fitted together using mainly electron beam welding. Only the upper part(compression side of the wing) is bolted to the integral lower part(fig.10). On the lower side, to avoid potential fatigue problems, holes were avoided and seams were minimized.

Figure 10: Wing carry through box

The technology of electron beam welding(the welding process and quality assurance/controlling) and the allowable stress levels were worked out in comprehensive test series. Because of the removable upper part all welding seems are relatively easily accessible for welding, machining ,repair welding and crack detection.

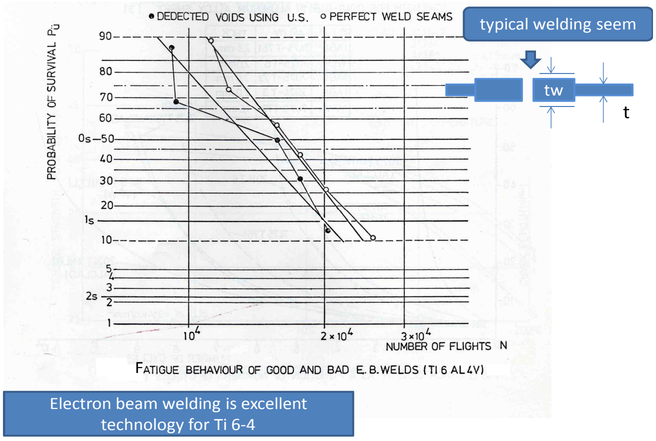

Figure 11: Life of eb welding seams

The development of the wing carry through box was by far more complex than the pivot as such. It is probably the most challenging metal structural part ever developed and built by German aerospace industry.[5]

Very early in the program the pivot system, including the wing carry through box, the Teflon coated sealing bags and the surrounding structure were fatigue tested(fig.12).

[5]Considering the front view of the Tornado, not much room is left for structures. Here the classical conflict drag versus weight was very pronounced.

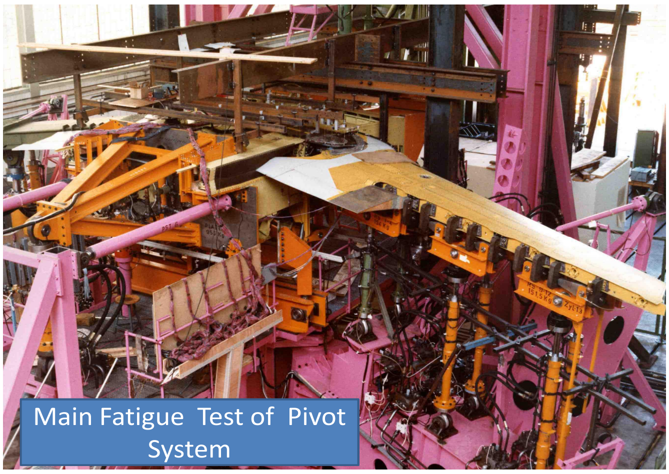

Figure 12: Major fatigue test

Fig.13 is a picture of the first prototype, which shows in some detail some of the features I have tried to highlight.

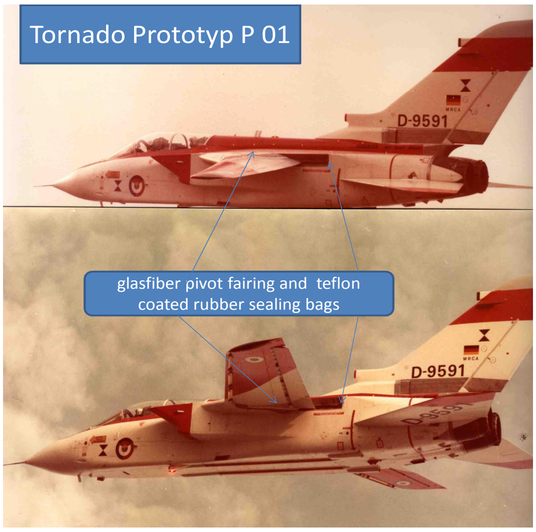

Figure 13: Tornado prototype P01

1.4 Summary

The Tornado weapon system,which was developed and produced by the *British, Italian and German Industry,* was besides the Eurofighter probably the most complex European military aircraft program. Close to 1000 Aircraft have been built and many of them, 40 years after the first flight, are still in service and will continue for years to come.

Of course there would be much more to be reported about this story of success, but I limited myself to concentrate on VG issues. *To my knowledge the swing wing system did not cause any major problem so far and the Tornado still is a reliable and powerful weapon system.*

2 Bo 108/EC 135 Bearingless Main Rotor

2.1 Articulated Rotor

The development of helicopters, mainly because of their mechanical complexity was lagging behind aircraft. But in the late 50ies, early 60ies a certain level of maturity was achieved and the helicopters started to find their roles. The most important part of an helicopter is the main rotor and each rotor blade is attached to the hub by 3 different hinges, allowing *flapping,lead lag and feathering movements* of the individual blade.[6] Fig.14 shows the principle, for simplifying reasons considering only the flapping motion. Around the flapping hinge the aerodynamic and centrifugal forces acting on the individual blade are balanced.[7]

[6] Famous helicopter designers expressed the opinion that only the parts above the swash plate are fun!

[7] The action of the centrifugal forces in combination with the flapping hinge avoids bending and this is the main reason, why rotors are relatively not heavier than wings.

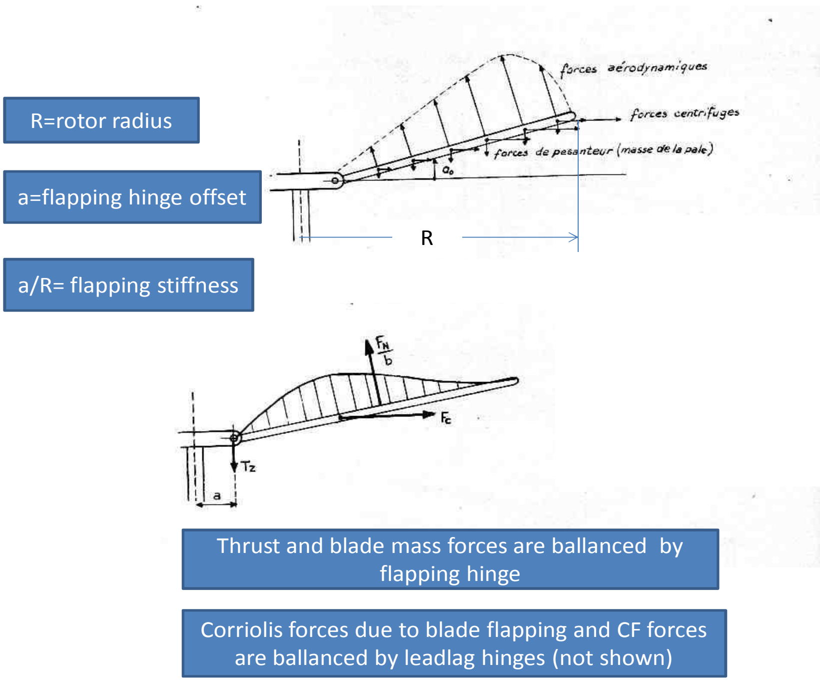

Figure 14: Principle of flapping hinge

The next picture shows a *state of the art articulated rotor*, where one can see all 3 hinges and in addition the lead lag dampers, which are necessary for this type of rotor(Fig.15). It is a master piece of engineering, but it is *complex, expensive and control response of such rotors, at least at some flight conditions,may have drawbacks.*[8]

[8]At flight conditions with low or negative load factors articulated rotors lose control power. Military helicopters however, which have to operate at lowest altitudes, can not avoid such situations.

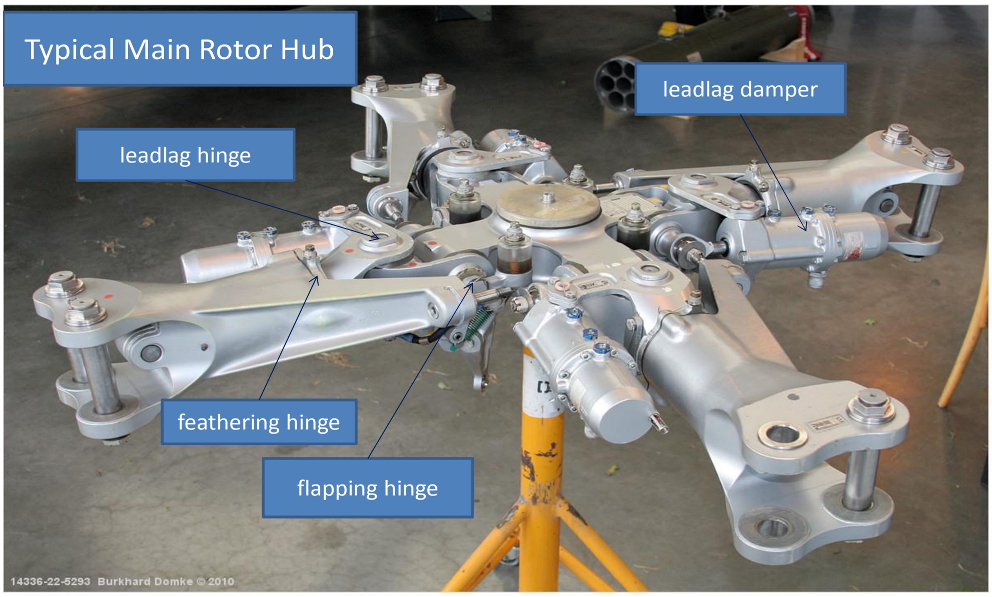

Figure 15: Fully articulated main rotor

2.2 Hingeless Rotor

In 1963 I started my career as engineer working in the helicopter department of MBB[9]. Despite being newcomers to this industry, it was decided not to take a license of a foreign helicopter, but rather develop an own machine. This is how the Bo 105 program started, which subsequently became a success story and can be seen as the *rebirth of German helicopter industry* after the war. One of the new features of the Bo 105 was a *hingeless main rotor in combination with glass fiber reinforced rotor blades.* The hingeless rotor tries to avoid the flapping and lead lag hinges by attaching the flexible blades directly to the hub. This of course was a significant deviation of the state of the art. Because of the *potential benefits(simpler,less expensive,better maneuverability)* many companies tried to develop rotors without hinges. But nobody succeeded to full production. Fig 16 shows schematically the difference to articulated rotors, as highlighted before

[9]Before and during the second world war Germany was pioneering helicopter technology. Because of the lost war work on helicopters was interrupted for nearly two decades

in fig.14

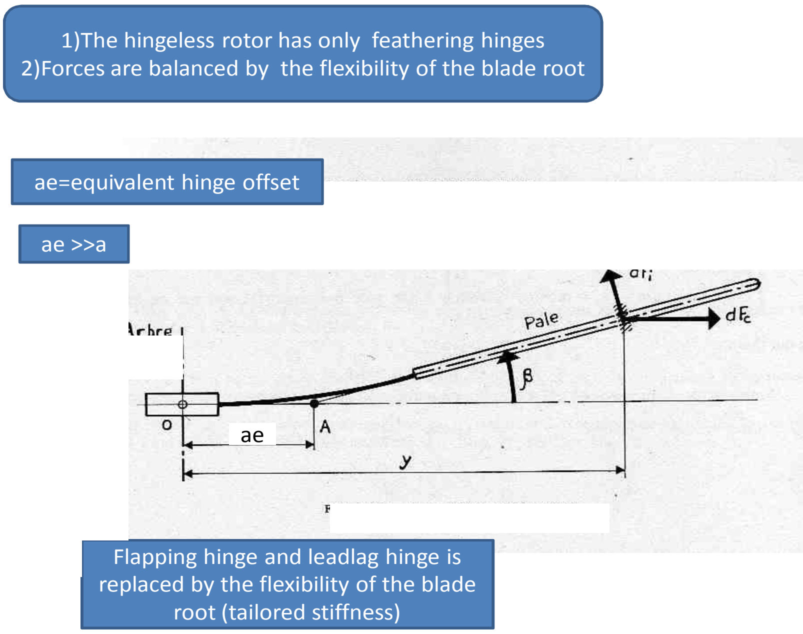

Figure 16: Principle of hingeless rotor

In this context it has to be mentioned that there was no practical experience, no theory and even the certification rules did not care about hingeless rotors. To make a long story short, by tremendous enthusiasm, hard work and maybe good luck,we were successful and pioneered helicopter technology again. *The key element was the glass fiber reinforced blade* which allowed the *aeroelastic tailoring at the blade root.* Also here many "experts", this time worldwide, predicted that we will fail. Nevertheless, the hingeless rotor with glass fiber reinforced blades became a full success(fig.17). Today glass fiber/composite blades can reach unlimited life and may be used on condition. They became a worldwide standard.[10]

[10] In the 60ies there was a cooperation between France/AS and Germany/MBB and design verification flights were performed on an Alouette II, being equipped with a MBB hingeless rotor. Today both partners are the main players of Airbus Helicopters. In addition there was also a cooperation with Boeing Vertol. Initially Boeing gave support to us. Later they took a license of the Bo 105, including blade technology.

Figure 17: MBB's hingeless rotor

Besides the simplification of the system also the control response was improved considerably. This is best demonstrated by the fact that pilots of the German Army Aviators won 3 times in series the helicopter aerobatic championship using the military Bo 105M(VBH) with the described hingeless rotor. Even today, about 50 years after its first flight, *the Bo 105 still is the most maneuverable manned helicopter ever built(fig 17).* About 1500 helicopters were built and today more than 600 helicopters are still in world wide operation.

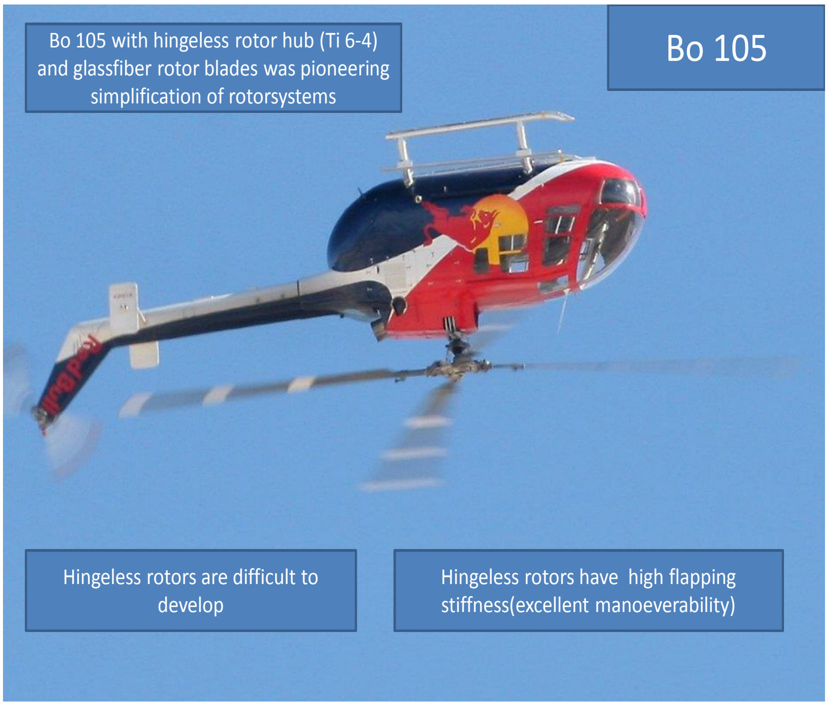

Figure 18: Bo105 of Red Bull

Subsequently the hingeless rotor with his glass fiber reinforced blades was adapted for the bigger BK 117.[11]

[11]The BK 117 started as a joint program of Boeing, MBB and Kawasaki. Because of other priorities(UH 70 program competition in the USA) Boeing withdraw. Fortunately MBB and Kawasaki decided to continue without Boeing. Ironically, Boeing lost the UH 70 competition against Sikorsky. Today however, the US Army operates several hundred BK 117/EC 145 helicopters (UH 72).

Figure 19: UH 72, using a hingeless rotor

After the success of the Bo 105 more or less all helicopter manufacturers were working on glass fiber/composite rotor blades and on rotor systems with reduced complexity.[12]

2.3 FEL Rotor

The hingeless rotor of the BO 105/BK 117 still has oil lubricated needle bearings for the feathering motion and for the rotor head Titanium 6-4 is used.[13] Over the years, especially with new programs such as the Tiger helicopter, we wanted to get rid of the oil lubrication and of the relatively expensive Titanium. Especially for the Tiger the German Army wanted similar flight characteristics to the Bo 105, but better battle damage tolerance than with a metal hub. Therefore the hingeless

[12]For large helicopters hingeless rotors may become unpractical. A good solution in this case are articulated rotors with cardanic blade attachments using elastomeric bearings. Here the flapping and lead lag takes place in one hinge.

[13]The rotor hub for the Bo 105 and the Tornado wing carry through box probably were the first really important structures using Titanium 6-4 in Germany and maybe in Europe.

rotor for the Tiger was developed into this direction. The main rotor consists of basically two composite star parts carrying maintenance free elastomeric bearings for the feathering motion. Flapping and lead lag is again allowed by the tailored stiffness and strength of the blade root(fig 19).

Figure 20: FEL rotor

The next picture(fig.20) shows the Franco-German Tiger attack/antitank helicopter equipped with an FEL hingeless rotor assuring the required maneuverability. This program, besides its military importance, is insofar very important, as it was a joint development between AS and MBB . Out of this cooperation the world leader Airbus Helicopters(formerly EC) evolved.

Figure 21: Tiger attack/antitank helicopter

2.4 Bearingless Rotor

Fig.21 shows a comparison between *hingeless* and *bearingless* rotors. For the bearingless rotor the blade is attached to the hub in such a way *that the flexible blade root allows all three motions.* Another important requirement is the introduction of the static and cyclic torque around the feathering axis to the blades. *One needs an aerodynamically smooth structure, soft in bending and stiff in torsion.* Unknown was, whether the structural in plane damping is sufficient to avoid lead lag dampers. The hingeless rotors are in this respect marginal. Bo 105 and BK 117 can do without dampers,whereas the Tiger needed them.

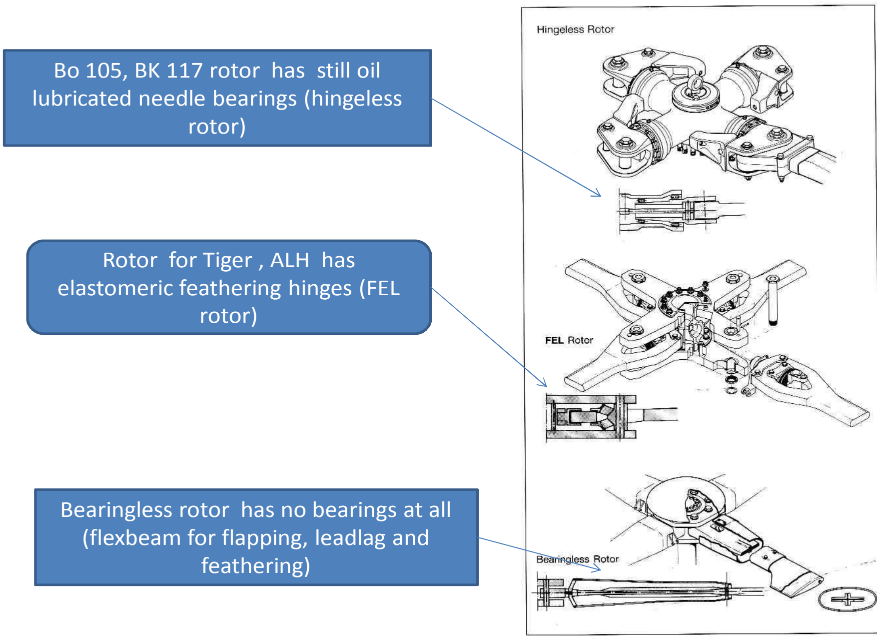

Figure 22: Hingeless and bearingless rotor

In the early 80ies MBB began with trade offs of a modernization of the Bo 105 or an totally new replacement helicopter. *Finally we decided for a new helicopter dubbed Bo 108.* For this helicopter we wanted among many other novel features a fully bearingless rotor. Because it was clear to us that in time development of such a technological challenge was bearing high risks, it was done parallel to the helicopter development. In case of failure or undue delays the hingeless rotor with aerodynamically improved blades was the back up. Fig.22 show the development steps leading to the bearingless rotor.

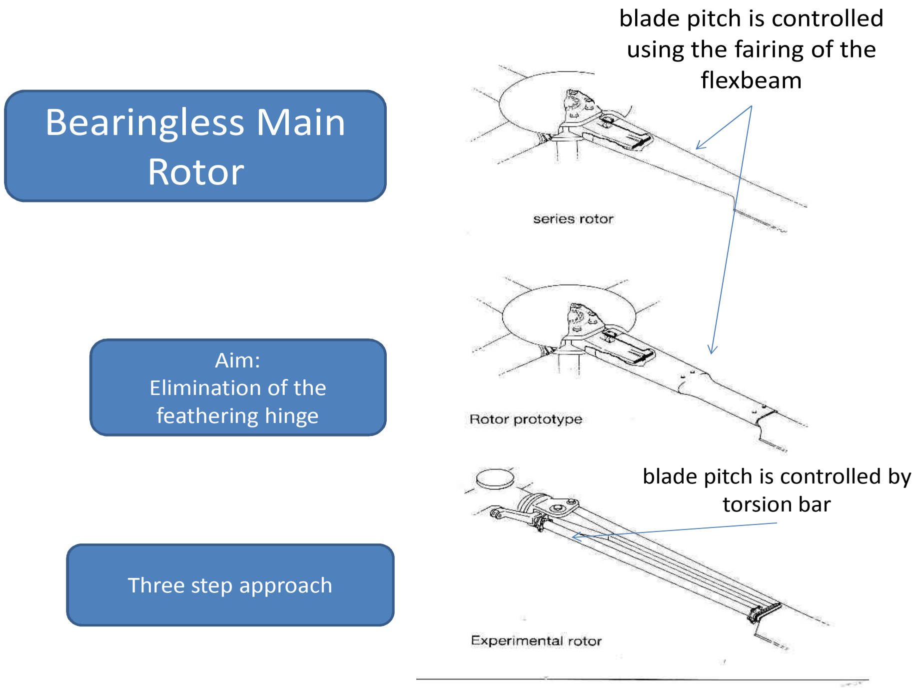

Figure 23: Development steps of bearingless rotor

The first step was a crude in flight verification test proofing the feasibility. Using a Bo 105 with fixed feathering bearings on the hub, attaching the blades via a relatively long flex beam and introducing pitch control by torsion rods, we covered in flight tests the basic flight envelope of the Bo 105(fig.23, upper picture). During these flight tests, in line with the Bo 105 and BK 117 experience, lead lag dampers were not necessary. There were no indications of air or ground resonance. Nevertheless, to be on the safe side, we decided to use integrated rubber devices to add damping to the natural aerodynamic and structural damping.

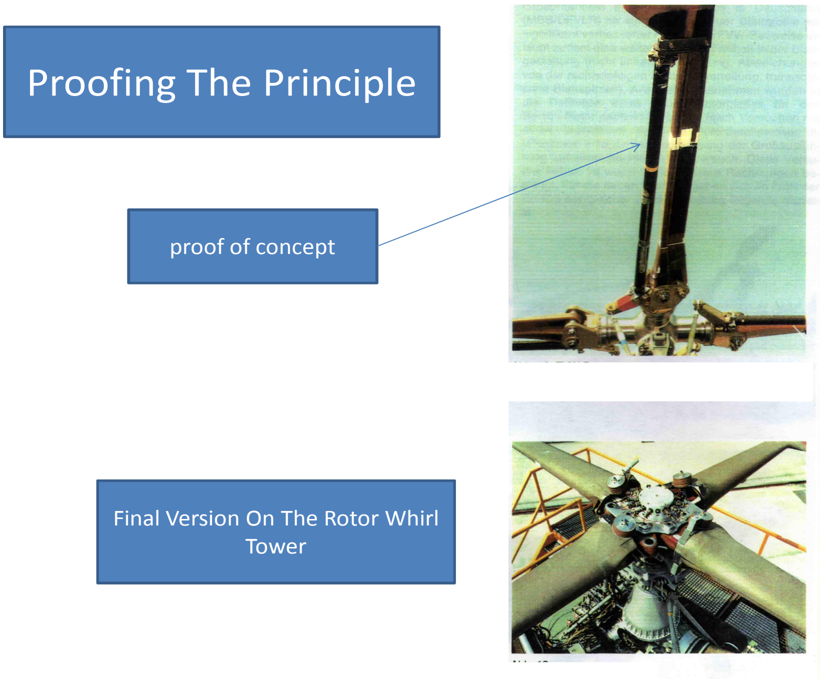

Figure 24: Proof of concept

The next step was a prototype of the wanted configuration with the flex beam of the blade bolted directly to the rotor shaft. By doing this the rotor hub is replaced by a double flange carrying the blades. The aerodynamically ugly flex beam was smoothed by an elliptically shaped fairing. Via this fairing the torque was introduced to the blade. The fairing was made of two parts to allow for checking of the flex beam(see fig.24). This Prototype was thoroughly tested on the relevant whirl tower and parallel in flight tests on the BO 105.

Figure 25: Prototype of bearingless rotor

Parallel to the development of the Bo 108 helicopter the final version of the bearingless rotor was designed.In fig. 23 the lower picture shows this final version on the whirl tower. In the fall of 1987 the helicopter *Bo 108 and the bearingless main rotor*[14] were ready for flight testing(fig.26).

[14]The Bo 108 was the last MBB helicopter and was the basis for the successful EC 135. After the fusion between AS and MBB the French Fenestron tail rotor was introduced, adding operational safety and reducing tail rotor noise.

Figure 26: Bo 108 and EC 135

The last picture shows impressively *the simplicity of the end product.* The advantages are numerous. Mainly:

- utmost simplicity
- significantly less weight
- significantly reduced parts count and no hub at all
- practically no maintenance
- possibility for on condition operation

Figure 27: Bearingless Rotor

2.5 Conclusion

The development of the bearingless main rotor was one of the most challenging tasks performed by helicopter industry. The task was extremely complicated, but the result is in my opinion convincing. To speak with Steve Jobs: *"Simplicity is the ultimate sophistication".* From the EC 135 today more than 1200 helicopters are in worldwide operation. The EC 135 is the market leader in the class of light twin engine helicopters.

3 Appendix

3.1 CV/von Tein

Prof. Volker von Tein

Year	Programs	Comp.	Functions
1963-1971	BO 105 Helicopter	MBB	Design, Test, Certif.
1971-1981	TORNADO Techn./Concepts for Eurofighter	MBB	Design,Strength,Test Progr.Manager Senior VP Engineering
1981-1990	BO 108(EC 135) BK117(EC145) TIGER NH90	MBB	Senior VP Engineering General Management
1990-1993	Hermes, Sänger Ariane 4,5 Satellites	MBB DASA	President and General Manager
1993-1998	A 319/320/321 A330/340 A3XX A400M	AI	COO
1998-2002	Research(AC and Energy)	DLR	Member of Executive Board
2002-2006	German Helicopter Operators	DHV	President

Helicopters
Aircraft
Space

3.2 Presentation at Air and Space Academy

Two Examples For Engineering Challenges

1) Tornado Wing Pivot
2) Bo 108/EC 135 Bearingless Main Rotor

Volker von Tein

13.6.2013

Air and Space Academy

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