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European Union Aviation Safety Agency

SMART GREEN AND INTEGRATED TRANSPORT

Integrity improvement of rotorcraft main gearbox

An Agency of the European Union

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EVALUATE AND DEFINE ROTOR AND ROTOR DRIVE SYSTEM DESIGN OPTIONS TO PREVENT SINGLE POINTS OF CATASTROPHIC FAILURE

Stream 1: Summary and conclusion report

Airbus Helicopters Technik GmbH

Airbus Helicopters Technik GmbH is a worldwide company known for its helicopter transmission systems. With our EASA and FAA privileges we are active for design and development, manufacturing and maintenance of helicopter transmission systems and geared applications for fix wing aircrafts and engines. Our service activities are not only keeping transmission system components airworthy, also mission support for a broad range of customers are conducted. For nearly all helicopter manufacturers around the world, Airbus Helicopters Technik GmbH designs and supplies worldwide turn-key solutions for gearbox and rotor test stands.

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SUMMARY

Problem area

The aim of this report is to identify potential alternative configuration options and to list general recommendations for helicopter main gearbox architectures to minimize, wherever possible, the number of catastrophic failure modes [5] in accordance with the objectives of the contract between EASA and AH Tech [2], and the EASA tender [1] based on the Horizon 2020 Work Programme Societal Challenge 4 'Smart, green and integrated transport'.

Description of work

As part of Stream 1 of the project, (dis)advantages of MGB architectures in D1-1 [5] (MGB architecture level, as well as the subassembly level) and design weaknesses have been identified and outlined. On this basis, alternative concepts have been evaluated and presented with the aim of minimizing the criticality of weaknesses, as well as demonstrating the effectiveness using failure flow diagrams for alternative concepts in D1-2 [10]. Also the applicability of alternative concepts according to CS-27 [3] and CS-29 [4] was reviewed. This report summarizes the outcome of Stream 1.

Results and application

The design rules and associated alternative design concept ideas were presented in report D1-2 [10]. Furthermore, [10] reports the evaluation of alternative design concepts for single applications using the same failure flow diagram and criticality analysis as in D1-1 for existing designs [5]. This alternative design concepts were compared to initial designs. The integration of one or several of these proposed design changes was then evaluated for different MGB architectures and for different parts of the MGBs that have been studied.

Table 1 proposes general MGB design recommendations, presents dedicated solutions within the scope of this project, summarizes remarks on the general feasibility and main disadvantages of the related concepts, and proposes a prioritization of concepts based on economic aspects of design (where possible). The prioritization also reflects the most promising solution. Nevertheless, ultimate applicability would have to be reviewed during the development of a dedicated design.
In summary, it can be stated that the alternative concepts under evaluation can be feasibly applied. On the other hand, even if the proposed solutions would help to prevent single points of failure or to reduce risk, it may be a challenge to implement them due to nearly unavoidable influences on size, weight and expected additional quantity of parts, which in turn may reduce analytical reliability and the ability of the MGB to fulfill aviation authority requirements. Ultimately, some of the proposals are widely known and have to be adapted to the specific design situation.

Design recommendations for H/C MGB configuration(s) conclude by identifying their weaknesses and proposing alternative design solutions for individual components or assemblies that can be used to prevent or at least minimize the number of catastrophic failure modes, and to ensure that the consequences of single failure modes are limited to loss of drive.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
AH Tech	Airbus Helicopters Technik GmbH
CAT	Catastrophic
CS	Certification Specification
EASA	European Union Aviation Safety Agency
FAR	Federal Aviation Regulations
H/C	Helicopter
HAZ	Hazardous
MGB	Main Gearbox
MTOW	Maximum Takeoff Weight
OEI	One Engine Inoperative
RCF	Rolling Contact Fatigue
SPoF	Single Point of Failure
ZF	ZF AG
ZFL	ZF Luftfahrttechnik GmbH

1. Introduction

The aim of this report is to identify potential alternative configuration options and to list general recommendations for helicopter main gearbox architectures to minimize, wherever possible, the number of catastrophic failure modes [5] based on the contract between EASA and AH Tech (formerly ZFL) [2] according the EASA tender [1] based on the Horizon 2020 Work Programme Societal Challenge 4 'Smart, green and integrated transport'.

As part of Stream 1 of the project, this was done by outlining the (dis)advantages of MGB architectures in D1-1 [5] (MGB architecture level, as well as the subassembly level) and identifying design weaknesses. Based on the examples identified in D1-1 [5], alternative concepts have been evaluated and presented to at least minimize the criticality of weaknesses, as well as to demonstrate the effectiveness using failure flow diagrams for alternative concepts in D1-2 [10]. Also the applicability of alternative concepts according to CS-27 [3] and CS-29 [4] was reviewed. This report summarizes the outcome of Stream 1.

The outcome of this analysis shall be, at minimum, general recommendations for design evolution of MGBs.

Chapter 2 explains the methodology used for the evaluation of alternative concepts and reviews the results of D1-1 and D1-2.

Chapter 3 summarizes the information and states a recommendation based on the results.

2. Stream 1 activities and explanation of methodology

In Stream 1 of the project, the objective was to evaluate state-of-the-art rotor and rotor drive system configurations as well as potential alternative configurations; and to determine system architecture and individual component design recommendations to prevent single points of catastrophic failure. Wherever possible, the consequence of any failure mode resulting from the failure of a single component of the rotor and rotor drive system should be limited to loss of drive.

2.1 Evaluation of design architectures

The first step was to study drive system configurations. Therefore, several analyses were conducted to evaluate different configurations present in existing rotorcraft whose purpose is to split the reduction ratio across the various transmission components. The analyses furthermore sought to achieve a design for maximum transmission analytical reliability while fulfilling weight and configuration requirements. [12]
This investigation shows first that there are two ways of transmitting the power of an engine to the main rotor using the MGB. First, the power is transmitted by one or more input and intermediate stages, collected by a bull gear and further transmitted to the rotor mast (collector architecture). Second, one or more epicyclic/planetary stages additionally reduce the ratio (epicyclic architecture).
In the following, several example configurations on epicyclic and collector architecture have been described and summarized with respect to MTOW, configuration and certification (in accordance to CS, FAR, etc.), ratio, stages, gear technology as well as bearing configuration. [5]
Main failure modes from damage catalogues based on the structure of [16] and on the information available in various public literature (such as [13]), as well as on experience ([14], [15]) have already been described. This treatment deals with a wide range of failure modes and their wide range of mechanisms.
Each different cause of failure produces its own characteristic damage. Such damage, known as primary damage, gives rise to secondary, failure-inducing damage, flaking, and cracks. Even primary damage may necessitate scrapping of parts due to excessive clearance/backlash, vibrations and noise, for example.

The consequence of the failure may lead to catastrophic breakage if it remains unnoticed. Regardless of when the trouble is rectified – in the design or re-design stage – the most important aid to the designer is the ability to recognize the exact type of incipient failure, how far it may progress, and the cause and cure of the problem. [5] summarizes causes and distinguishes between major and minor causes based on experience regarding gearing, as well as on observed damage resulting from failure modes on planet bearings at project partners. In addition to regular known failures and mechanisms, in-service and MRO experience was also summarized.

The literature survey and analysis of publicly available data and documentation found some relevant examples of incidents and accidents involving MGB failures which in turn led or may have led, under different circumstances, to catastrophic failure. All the events found had a connection to designs featuring epicyclic architectures. By contrast, the survey found no catastrophic failures resulting from MGBs used within collector architectures. All summarized events and assessment thereof are derived exclusively from the aforementioned public sources. The resulting experience has been taken into account and used as valuable input for further analysis.
Therefore, single points of failure (SPoFs) have been identified that could lead to catastrophic failure at the rotorcraft level. The analyses described in [5] were used to identify these single points of failure and the possible causes and failure mechanisms leading up to them, based on specific examples from existing designs.

By reviewing the described failure modes with regards to their effect on catastrophic failures modes, the causes have been summarized as

- Inappropriate design assumptions
- Lubrication issues such as loss of oil and/or oil pressure, and/or friction due to contamination
- Material defects
- Manufacturing defects
- Lightning/electrical power damage
- Excessive wear
- Assembly failures

Some of these causes have been applied to multiple architectures within a failure flow analysis, pointing out the catastrophic paths on the basis of categories and definitions according AC29-2C [18]. The analysis was done based on several assumptions due to a lack of detailed design information. Therefore, some causes were not considered or were only partly considered (e.g. seizure of bearings, excessive wear, inappropriate design assumptions, etc.).

Within this project, failure criticality analyses were used for predefined gearbox architectures in order to detect critical load paths with a risk of single points of failure (SPoFs). The models were chosen as a good representation of current helicopter models with different technical solutions for each gearbox architecture analyzed (e.g. gearbox architecture with planetary gear stages, gearbox architecture with a collector gear stage, single engine system and a variant with split torque load paths and a double collector stage).
To detect SPoFs within the aforementioned architectures, a top-down methodology was chosen (Figure 1).

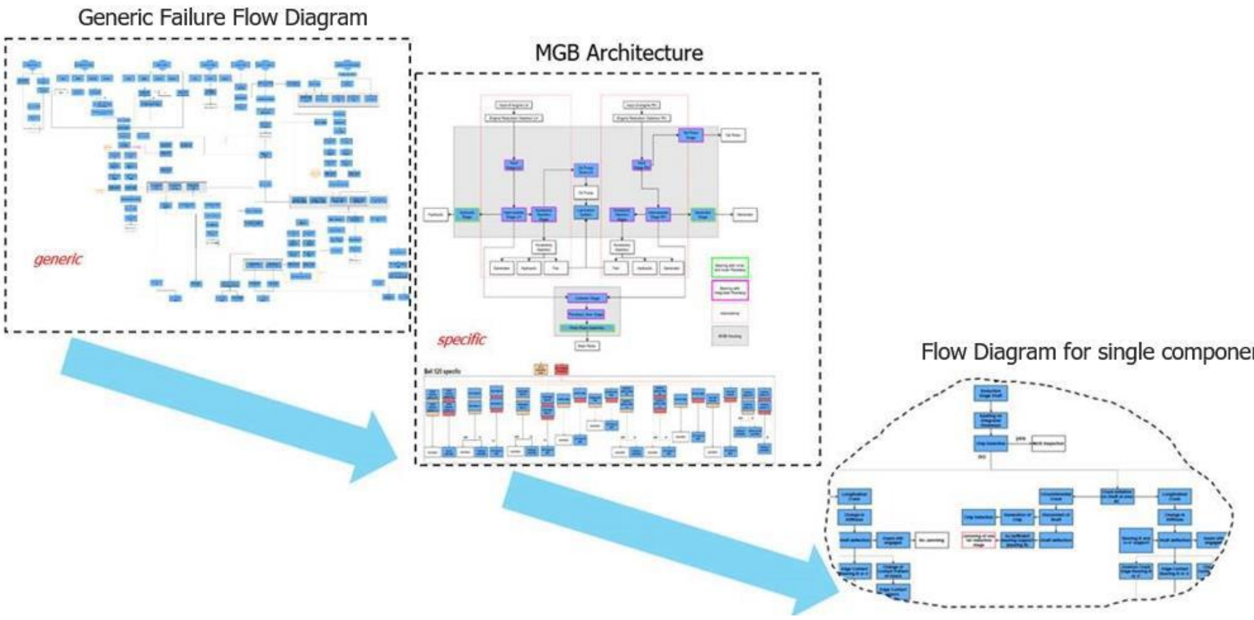


Figure 1: Flow diagram approach

The top-down methodology starts with a generic failure flow diagram, which could be used and implemented for each gearbox architecture, giving an overview about general gearbox failure mechanisms and their respective root cause. This generic approach can be seen as a starting point and was used to discover critical load paths, their causes, and their effects regarding the safe flight and landing capability of the H/C.
In the second step within the top-down methodology, more specific work was done. Diagrams of the gearbox architectures were made to get an overview of the different components inside the gearbox, their connections, and the load path. The gearbox architectures show the system and gear stages inside the MGB (Figure 1, colored in blue) and the components/systems outside the gearbox (Figure 1, colored in white) on the assembly level. Moreover, components with integrated bearings or standard bearings were marked and redundant load paths highlighted. In addition to the generic failure flow diagram, which is identical for each helicopter type, a

specific part was introduced able to detect redundancies inside the gearbox drive train and evaluate the failures according to the criticality and effects on the safety of the helicopter. In this case, the two main failure results ("loss of transmitting power" and "loss of integrity of the component/stage") are used to show what will happen if one of these failure mode arises. As a final step, and based on this generic and specific pre-work, failure flow diagrams were made for all main components of the gearboxes with the potential for catastrophic failures (Figure 1, right).

The single component flow diagrams are structured as presented in Figure 2. The component and the corresponding failure mechanism is given at the top level. As a result, the different failure causes are shown, ending in final events (white background). The final events are divided into non-catastrophic (black box) and catastrophic events (red box). Catastrophic events will lead to a catastrophic failure of the MGB if there is no redundancy or other safety barrier interrupting the failure progression. A catastrophic failure does not strictly lead to loss of the rotorcraft: a safe landing may be possible depending on the flight conditions. This flow diagram of the single components was later used to define the single points of failure (SPoFs) and define suitable design measures to avoid catastrophic failures.

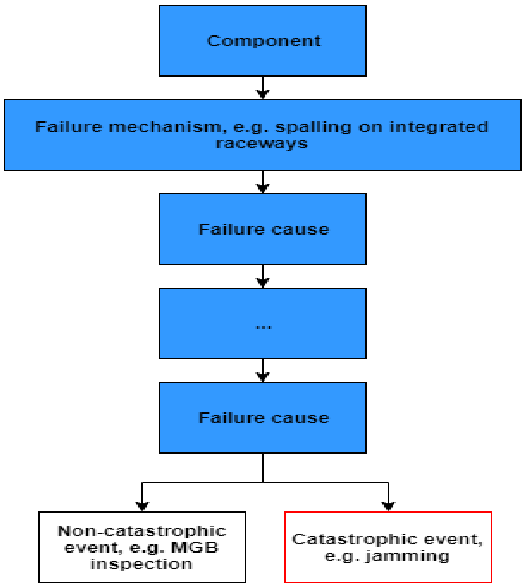


Figure 2: Structure of failure flow diagrams

Some assumptions were made for all failure flow diagrams due to the lack of detailed design information. More detailed information may possibly lead to a less critical result. Nevertheless, as fundamental design information is not known, it is difficult to draw conclusions about failure criticality. Generally, the most conservative failure classification was used.

The detailed design of each drive system section, affected by a certain failure mechanism, plays a fundamental role for the consequences and severity of the failure. Relevant for this are in general the following points, which could even work as a safety barrier:

- Design
- Redundancies
- Installation space
- Design of interfaces/connection points
- Gearbox type/architecture

The output of the generic flow diagram was used as an input for the specific failure flow diagrams, where the influence of the failure modes at a certain MGB stage/component and their final impact on the safety of the helicopter's flight were evaluated. The critical components and all other components of the main load path were further analyzed through detailed component diagrams to underline the statements made for the specific examples.

The catastrophic weaknesses and their positions in the evaluated configurations have been summarized in Annex A.1 to A.5 of D1-1 [5]. All of the listed cases lead to the loss of the normal distribution of loads from input to output stage, followed by a catastrophic event.

By elaborating upon the failure flow diagrams and reviewing cases in connection with identified design weaknesses, causes leading to jamming, loss of transmitting power or loss of the rotor mast itself can be highlighted. The contributing factors in designs experiencing catastrophic breakage and/or cracking can be summarized in the following way:

- Ejection of fragments from gear mesh not possible, which could subsequently lead to additional damage
- Release of fragments and damaging of other gear stages by overrolling
- Insufficient support from (for example) bearings and hubs of parts after breakage culminating in jamming due to deflection/movement of fragments/parts. In some cases this is signaled by excessive noise and vibration.
- Incorrect gear reengagement due to loss of a single tooth or multiple teeth, leading to jamming of the gear or loss of transmitting power
- Total wear of spline leading to loss of transmitting power to the main rotor or tail rotor
- Radial, circumferential or longitudinal cracks leading to a disconnect in the power transmission path or jamming due to increased deflection or deformation of components

As a result of the assessment, it was shown that circumferential and radial cracks or tooth breakages could lead to jamming or disconnection within the load path. Mainly for shafts, longitudinal cracks lead to a reduction in stiffness rather than disconnection or jamming, and therefore they do not lead to catastrophic events as often as circumferential or radial cracks. Longitudinal cracks at the rotor mast are an exception by consideration of catastrophic events. It is also assumed that a stiff bolted connection could reduce the risk of catastrophic failures resulting from radial cracks. Additionally, it is shown that tooth breakage does not automatically lead to a disconnection of load transmission but rather contributes to jamming if the broken parts cannot be ejected. Nevertheless, it is important to explain that this evaluation is restricted by assumptions and data limitations:

- Assumptions about the design solutions due to limited access to original design data
- Simplification of failure mechanism, e.g. radial, circumferential and longitudinal cracks as representative of all crack types
- Assumptions about failure behavior and consequences for the power transmission or component integrity
- Failure modes and mechanisms based on and limited to AH Tech experience as well as public data

Consequently, it is not possible to identify all possible catastrophic failure modes for all of the analyzed gearbox examples. Rather, the objective is to identify potential design weaknesses that can be improved and/or avoided by general design solutions and modifications to the MGB architectures within the scope of this research project.

There are still other situations which could potentially lead to catastrophic events and which were not part of the failure flow diagram evaluation, since they are not part of the main transmission path from input stages to output stages of a MGB. The analysis was moreover based on several assumptions and therefore the analysis may possibly fail to identify a catastrophic failure mode. Some public examples of this kind are part of the collection in [17].

2.2 Methodology to evaluate alternative design concepts

After considering the different MGB architectures and associated catastrophic SPoFs identified in the D1-1 report [5], design rules have been identified (e.g. design additional feature(s) to prevent jamming in shaft assemblies). Furthermore, preliminary ideas and concepts were developed in order to identify general design changes (e.g. the concept of a "Jamming Preventer" to avoid shaft jams) that could be applied to MGB designs to reduce the number of catastrophic SPoFs or at least provide some safety improvements. Some such improvements may include:

- Eliminate potential catastrophic failures from all flight conditions to specific failure or limit their severity for certain flight conditions
- Allow potential catastrophic failure outcomes to result instead from failure modes for which compensating provisions are easier to implement compared to the initial mitigation scheme

To reduce and/or rule out the risk of a catastrophic SPoF, the project proposes changes to existing MGB designs. Since it is uncommon to alter specifications of existing and certified MGBs to decrease the loads applied to them, the design of such MGBs has to be improved as necessary and based on a detailed analysis in collaboration with an aviation authority. For new developments, the design proposals can be incorporated from scratch. To this end, the following failure types (already identified in [5]) resulting in catastrophic consequences were considered:

[A] Jamming of shaft
[B] Jamming of planet in a planetary stage
[C] Jamming of another component
[D] Loss of transmitting power, but having a redundant power path, e.g. for emergency landing
[E] Loss of transmitting power to main rotor
[F] Loss of transmitting power to tail rotor and/or interconnection between main and tail rotor

In addition, the possible effects of each failure, assessed below in the document (e.g. with and without alternative design solutions), are described as follows:

- Failure effect I/HAZ-CAT: Loss of transmitting power with working tail rotor leading to loss of the ability to continue safe flight to a suitable landing site. Emergency landing with autorotation could be possible under certain circumstances (tail rotor intact). The damaged components rotate within the system without impacting the integrity of the housing and surrounding main components.
- Failure effect II/HAZ-CAT: Loss of transmitting power without working tail rotor leading to loss of the ability to continue safe flight to a suitable landing site. Emergency landing without tail rotor drive could be possible under certain circumstances (based on sufficient altitude and flight speed [9]). The damaged components rotate within the system without impacting the integrity of the housing and surrounding main components.
- Failure effect III/CAT: Loss of integrity of H/C. Uncontrolled landing: Loss of main rotor system and structural damage in terms of power flows from the engines to the rotors. Loads are transferred from the rotors to the airframe.

The following high level design recommendations should be considered in order to mitigate and/or rule out the risk of a catastrophic SPoF. An example of how to integrate these recommendations is provided in Figure 3. These recommendations have been used as inputs to propose alternative design solutions:

1. Dimension parts with adequate safety margins and in consideration of safety aspects
2. Design additional safety barrier(s) to prevent crack propagation into surrounding areas
3. Design additional feature(s) to prevent jamming in shaft assemblies (concept 5 in Annex A)
4. Design additional feature(s) to prevent jamming in planetary assemblies (concept 6 in Annex A)
5. Ensure that the most critical areas (e.g. having the lowest static and fatigue margins) of components are designed to accommodate foreseeable overloads
6. Design redundancy path(s)
7. Design emergency redundancy for the tail rotor drive (concept 9 in Annex A)

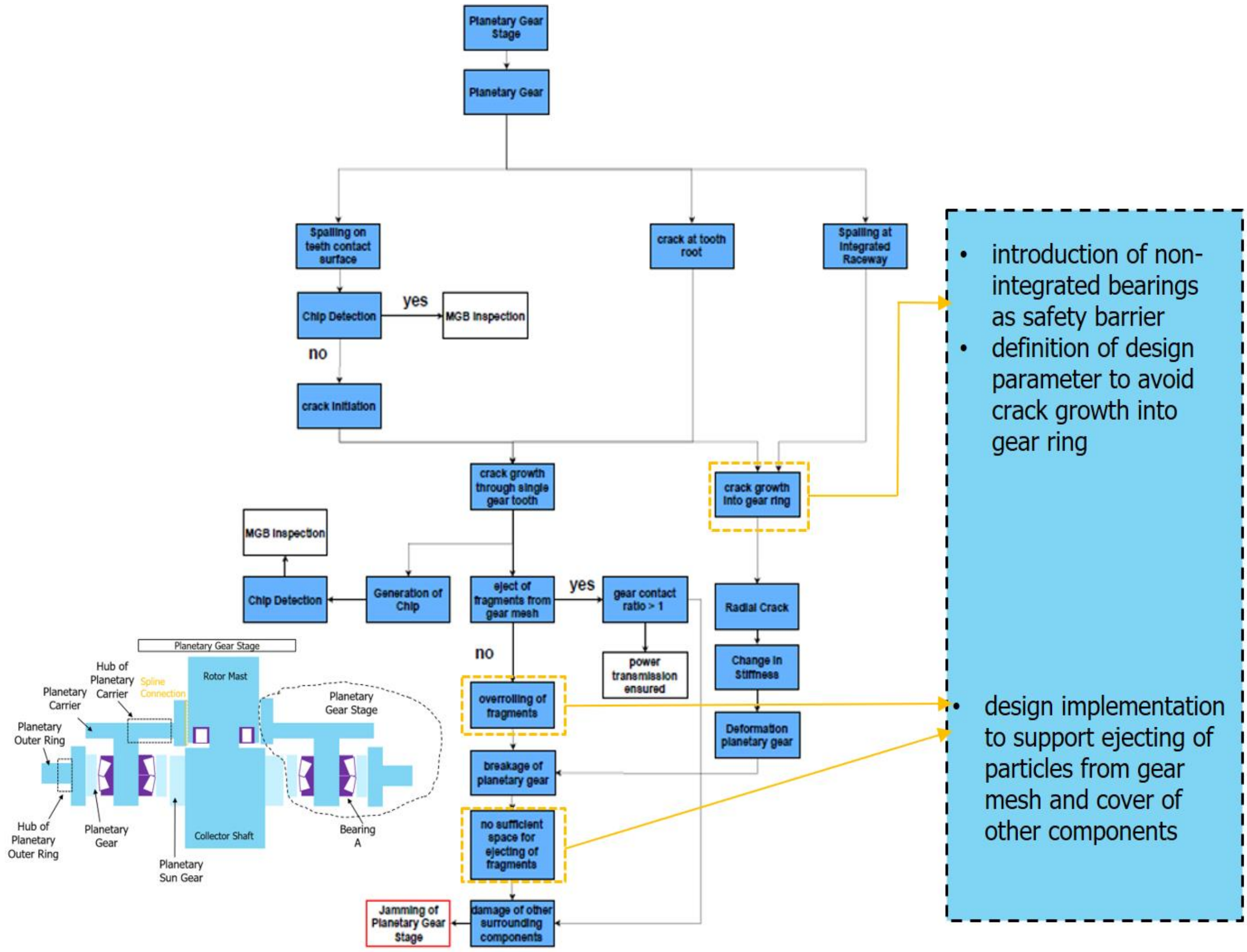


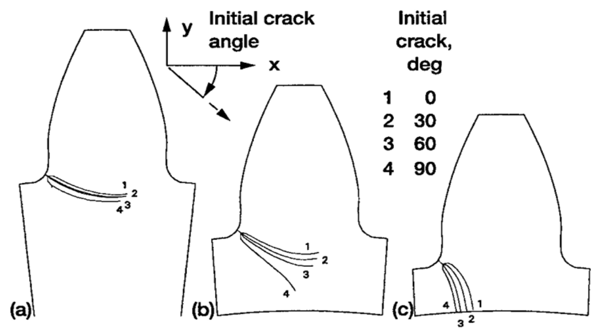
Figure 3: Introduction of a safety barrier

The design rules and associated alternative design concept ideas have been presented in D1-2 [10] and are described in section 3 of this report. Furthermore, [10] reports the evaluation of the alternative design concepts for single applications using the same failure flow diagram and criticality analysis as in D1-1 for existing designs [5]. This alternative design concepts were compared to initial designs. The integration of one or several of these proposed design changes was then evaluated for different MGB architectures (e.g. using one or two engines; using epicyclic gearing or a combining wheel) and for different parts of the MGBs under study.

3. Application and assessment of results

Table 1 proposes general recommendations when designing a MGB and dedicated solutions within the scope of this project. Secondly, it summarizes remarks on the general feasibility as well as the main disadvantages of the related concepts and proposes a prioritization order for the concepts based on estimated economic aspects of design. The prioritization also reflects the most promising solution. Nevertheless, the final applicability would have to be checked during the development of a dedicated design. In summary, it can be stated that the evaluated alternative concepts can be feasibly applied, even if they are challenging, particularly in the development of the final design. On the other hand, some of the proposals are widely known and would only have to be adapted to the specific design situation.

Even if the proposed solutions would help to prevent single points of failure or to reduce risk, it may be a challenge to implement them due to, in some cases, unavoidable influences on size, weight and/or expected additional quantity of parts and therefore a possibly lower analytical reliability and other needs of the MGB to fulfill aviation authority requirements. It must also be ensured that failure does not remain possible through other mechanisms. Proper quantification of these risks requires a dedicated design that can highlight the final influence, if any.

Priority of application	Rule recommendation	Alternative design solution	Assessment/Feasibility	Advantage	Main disadvantage
0-a	Dimensioning of parts with adequate/high safety margins to avoid design mistakes	This design rule recommendation should already be taken into account in the existing design solutions at least to show compliance to existing CS-27 or CS-29 requirements. These additional margins may not necessarily lead to a change of failure severity (which would remain catastrophic if initially identified as such) but this could help reducing the probability of failure of some components. In this respect, no specific alternative design solution are presented, as the resulting designs are easy to imagine (e.g. bigger parts).			
0-b	Dimensioning of parts to ensure that, in case of crack initiation, the crack would propagate in such a way that it would not result in catastrophic failure due to design mistakes	Gear tooth design: Cracks initiated on gear teeth, typically on the gear tooth root radius, could propagate into the body/web of the associated gear/shaft and lead to complete failure of those parts, in turn potentially resulting in catastrophic failure, if not properly designed. Even if the following design rule is already well known, it is worth mentioning that appropriate gear rim thickness should prevent cracks initiated on the gear root radius from propagating into the body/web of the associated gears/shafts, since the crack would only propagate into the root of the affected tooth. In case one tooth cracks completely, power transmission and/or free rotation of the affected parts could still be ensured, especially if enough space is available for the broken-off parts to be ejected without causing major subsequent damage to other parts or blockage of rotating parts. Nevertheless, best practice regarding heat treatment and grinding notches, for example, has to be taken into account during manufacture.  *Figure 4: Effect of Rim Thickness on Gear Crack Propagation Path [8]* Integrated bearing races: it is assumed that some bearing design parameters may help ensure that a crack initiated by RCF on a bearing race would either self-arrest or always turn back to the race surface (e.g. resulting in spalling). RCF crack paths, especially for integrated races, still need to be better understood and are the topic of the research done as part of Stream 2 of this research project – considering the parameters evaluated in D2-1 [6] and D2-2 [7] as well as the outcome based on D2-6 [11] of Stream 2 of this project in case of integrated raceways.	Feasible. These aspects should be the best way to design a MGB with the lowest possible risk for single points of failure. Nevertheless, the design requirements (e.g. design space and weight) would at minimum have to allow for this approach.	Lowest risk for SPoF	None in terms of safety. Unnecessarily high margins lead to weight increase, potentially affecting planned design space.

Priority of application	Rule recommendation	Alternative design solution	Assessment/Feasibility	Advantage	Main disadvantage
1-a (concept 4.1a and 4.1b in Annex A) 1-b (concept 4.2 in Annex A)	Ensure that cracks that could initiate on parts would be stopped (by design) to avoid potential catastrophic failures by means of additional safety barrier(s)	As it is difficult to completely prevent crack initiation on bearing races resulting from RCF, non-integrated bearing races could be used as an alternative design solution to integrated bearing races on shafts. This could ensure by design that those cracks would have to stop at race interfaces. This solution could be implemented in particular on the following parts to prevent potential catastrophic failure: - Planet gears with cage-type planet carrier and pin-type planet carrier - Shafts	Feasible. This is a well-known solution and is at least a part of current MGB architectures. Having non-integrated races requires increased design size, for example an increase in the planetary gears or a thicker rim for strength and analytical reliability purposes. This would sustain static and fatigue loads and minimize the potential risk of wear/fretting that could occur at the interface of the planet gear and the bearing outer race. Another aspect would be the integration of an anti-turn device.	This specific catastrophic failure can be lowered to a non-catastrophic failure * at the safety barrier provided by the transition between the inner bearing ring and the adjacent parts	Weight increase estimated around 110-118% of the original design as a result of reinforced and additional parts. Adding new parts may also reduce analytical reliability (e.g. increased risk of fretting and/or wear on new interfaces). New catastrophic failure mode: Gear/shaft crack through the interface with the new non-integrated bearing ring (e.g. due to fretting)
2-a (concept 5 in Annex A)	Design additional feature(s) to hold cracked parts of shaft assemblies in position to prevent potentially catastrophic jamming or blockage from broken-off parts	The support (jamming preventer) shaft is arranged inside the hollow shaft and is designed to hold the broken segments of the hollow shaft in position in the event of a shaft breakage in such a way that jamming or braking of the transmission is mostly avoided. The fact that the broken hollow shaft is supported by means of the support shaft within it prevents the broken segments of the hollow shaft from collapsing uncontrollably into the transmission. Since power can no longer be transmitted via the broken hollow shaft, the damage is quickly identified so that an emergency landing can be initiated. While on the one hand this does not ensure ongoing power transmission capability, it does prevent jamming.	Feasibility yet to be finally confirmed by a appropriate design. The support shaft is sleeve-shaped and secured axially on the inner peripheral surface of the hollow shaft with a mostly smooth outer peripheral surface (no application of structural details, e.g. teeth) and grooves on the outer peripheral surface for receiving a respective damping ring. In case of failure, the metal/metal support shall ensure relative rotation between the two pieces and provide sufficient emergency mode. It is assumed that the concept would then work only for specific failure modes (i.e. purely circumferential crack) and in specific areas of the shaft (where the jamming preventer can act). Principally, the application of this support shaft is possible on each shaft, but more probably not within high loaded shafts, e.g. rotormast, which would damage the jamming preventer.	This specific catastrophic failure can be lowered to a non-catastrophic failure for applications at least on MGB input, tail rotor output or intermediate shaft by keeping the shaft or its fragments in position in case of fracture.	Increase of weight due to the additional quantity of parts within the given design space. The magnitude of the increase depends on the given size of the related shaft. Due to higher complexity and quantity of parts by comparison with application 1-a/b, analytical reliability may also suffer more.
2-b (concept 6 in Annex A)	Design additional feature(s) to prevent jamming in planetary assemblies due to planet gear failures	Design planet gears with an “External emergency guide” to limit the deformation of a single-cracked planet gear and with the aim of ensuring correct gear meshing of the affected planetary gear train, avoiding jamming. The ability to retain fragments in case of further cracking may also be needed, considering that fragments will have a certain degree of freedom to move, which may prevent correct meshing of the teeth.	Depending on the load and deformation of the planetary gear set, there may be temporary contact between the support ring and the planetary gear. But only the case of lasting contact, e.g. by supporting the broken planetary gear on the support ring, would prevent the broken planetary gear from detaching from the carrier shaft and slipping into the gearbox in an uncontrolled fashion. Nevertheless, this would have to be applied in a dedicated design, as a final design of this application according the certification specification currently does not exist. This concept may strictly require detection of the failed part in order to arrest continued operation and further breaking of parts and/or release of fragments.	This specific catastrophic failure can be lowered to a non-catastrophic failure by preventing a blockage of the drive train. Thus, an emergency landing of the aircraft should be made possible in the event of a planet fracture in a transmission of the drive train.	Increase at least in size and the resulting weight of reinforced and additional parts, which would have to be evaluated in a dedicated design. As a consequence, analytical reliability may also suffer in the range of application 2-a due to its complexity.

Priority of application	Rule recommendation	Alternative design solution	Assessment/Feasibility	Advantage	Main disadvantage
Prio 3 (concept 7a and 7b in Annex A)	Ensure that a structural failure of rotating parts occurs at a pre-determined area (i.e. a "weak point") to ensure that the failure mode would still allow free rotation, thus preventing catastrophic failure due to jam/blockage by defusing the effect	Design a pre-determined shear section in shafts and planetary assemblies to control the probable crack location and path in case of very high overload (potentially as a result of jamming of another part). This would prevent an uncontrolled failure that may result in jamming/blocking of the MGB, which could be catastrophic. This controlled failure mode should ensure free rotation of the affected parts and should also ensure that there are no released fragments which may result in jamming/blockage of the MGB. If the shear section disconnects the mechanical link between the engine(s) and the main rotor, or the main rotor and the tail rotor, it is assumed that the failure consequence should still be considered catastrophic due to the potential loss of control of the rotorcraft in some flight conditions/operations. Nevertheless, this solution could be seen as a safety improvement if it prevents a loss of integrity of the main rotor (e.g. main rotor detaching from the rotorcraft), which would be immediately catastrophic in all flight conditions.	Feasibility yet to be confirmed. Possible in principle, provided it is possible to find a well-balanced design to ensure safe operation under normal conditions and also to limit maximum possible over-torque to a value that all the other relevant components can withstand. The maximum torque generated by the engines at the point shown is given by the engine and transmission and is certainly lower than the maximum possible main rotor inertial load. The other essential components (e.g. rotor mast bearing support) must be dimensioned in such a way that they do not fail under the breaking loads and any resulting damage must be withstood until landing is accomplished. The housing should be designed accordingly, and any other possible consequences should be taken into consideration since the rest of the MGB could jam due to the engine(s).	This specific catastrophic failure can be better managed in emergency mode, or the outcome can be less severe* since, due to the crack on the weakest point, the effect of the disconnected gear stage does not allow the jam to be transmitted to the rotor mast.	High complexity to develop a well-balanced design to ensure safe operation and loads. All parts need to sustain static and fatigue loads while still ensuring that the weak point or path will be the first critical area to fail under inertial loads of the main rotor in case a gear jams. In addition, an increase in size and weight of adjacent parts is probable. Analytical reliability may also suffer as a consequence.
Prio 4-a (concept 8 in Annex A)	Design redundant load path(s) to avoid full disconnection	Design a maximum number of MGB shafts with redundant load paths to ensure that, in case of a controlled failure (e.g. a failure not resulting in jamming such as when using a properly designed "shear section"), the redundant path would allow provision of power to the main and tail rotors. By ensuring that power is provided to the main rotor and tail rotor in case of failure of a load path, this solution would avoid catastrophic consequences in autorotation, which may be the case in some specific flight conditions. This design solution is already used for input shafts on multi-engine applications which are capable of operating in OEI conditions.	Feasible. Redundancies in MGBs are well known, especially for multiple load paths, but combined in only one main rotor mast. Hypothetically, redundant rotor masts could be developed with an aligned inner rotor mast turning direction, e.g. design principle similar to coaxial systems, but same direction of rotation. In practice, main rotor mast redundancy would only be feasible with great difficulty for reasons of weight and performance and may require ensuring detection of the failed part. For this case, feasibility yet has to be defined, since a design according the certification specification currently does not exist.	This specific catastrophic failure can be lowered to a non-catastrophic failure by decoupling the intact stages from jams.	Increase at least in size and the resulting weight of reinforced and additional parts. Analytical reliability may also suffer as a consequence. The more parts/stages are made redundant, the greater the impact on weight and reliability.
Prio 4-b (concept 9 in Annex A)	Design emergency redundancy for tail rotor drive to avoid full disconnection	Introduce an electric emergency tail rotor drive to ensure provision of power to the tail rotor in case of failure of the gear teeth of the MGB gear providing power to the tail rotor. The tail rotor thus has a redundant drive. The controllability of the aircraft around the vertical axis, that is, the yaw, would be maintained in case the drive connection between the main rotor and tail rotor fails. Because the electrical machine is operated in generator mode when the main gearbox is in normal operation and electrical energy is generated for the electrical system of the aircraft, a generator can be omitted at another point in the electrical system of the aircraft, so that essentially no additional weight is incurred by the electrical machine. The electrical machine is operated in motor mode in the event of a power failure in the main gearbox in order to generate drive power for the second rotor shaft. Multiple energy consumers and at least one energy storage device are arranged in the electrical system of the aircraft. The drive power generated during motor operation of the electric machine is routed to the tail rotor via the tail rotor drive train, causing the tail rotor to rotate.	Probably feasible. Additions to the MGB are not new in aviation systems, so this is in principle not an uncommon application. A drive-effective connection is to be understood as meaning that two components can be directly connected to each another or further components can be arranged in the power flow between two components. Consequently, two components that are connected to each another in a drive-effective manner can be connected directly, that is to say directly or indirectly, via other components arranged in between. Nevertheless, it has yet to be applied to a dedicated design, as a final design of the application according the certification specification currently does not exist.	This specific catastrophic failure can be lowered to a non-catastrophic failure by an external electric drive in case of emergency in the tail drive.	It is possible to keep weight increase to a minimum by replacing an existing part, but the total mass would be higher due to the more comprehensive requirement. Based on this, it might be possible to prevent a negative impact on reliability. Nevertheless, an increase of weight and quantity of parts for an additional energy storage device(s) will have a negative impact on weight and reliability.

Table 1: Application Assessment Prioritization Matrix of results

In conclusion, design recommendation of H/C MGB configuration(s) were evaluated by identification of their weaknesses and proposal of alternative design solutions of individual components or assemblies that can be used to prevent or at least minimize the number of catastrophic failure modes and to ensure that the consequences of single failure modes are limited to loss of drive.

4. References

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[5] D1-1: W. Riesen, Technical Note "Review of the state-of-the-art rotorcraft gearbox configuration and component designs", 30 July 2021

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- D2-3: W. Riesen, “Initial Test Plan”, 02 December 2021
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- D2-5: R. Boukellif, “Critical threats and crack development”, 12 July 2023
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Annex A Alternative Concepts

Some of the concepts based on pending patents within the scope of the project contract [2].

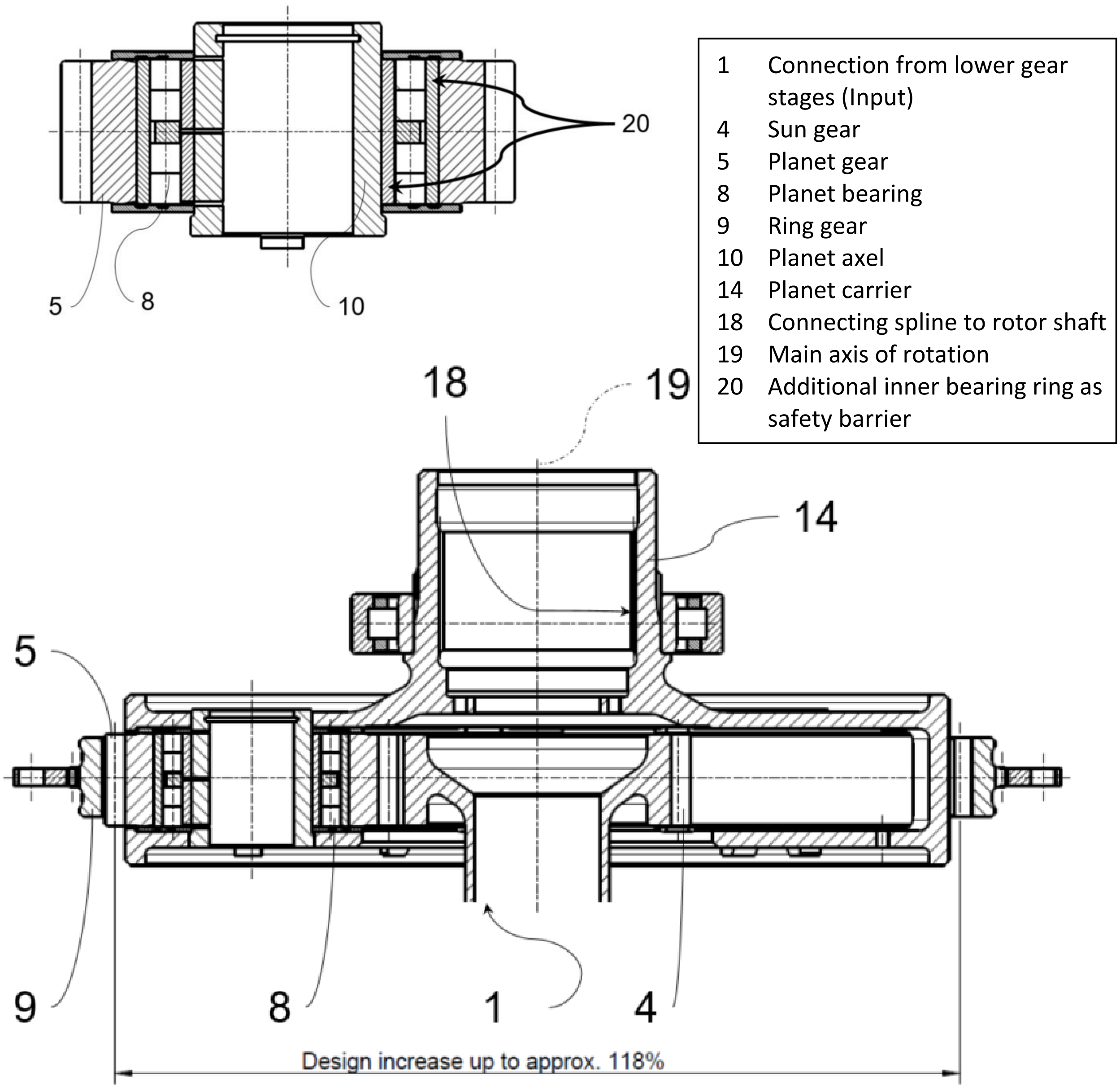
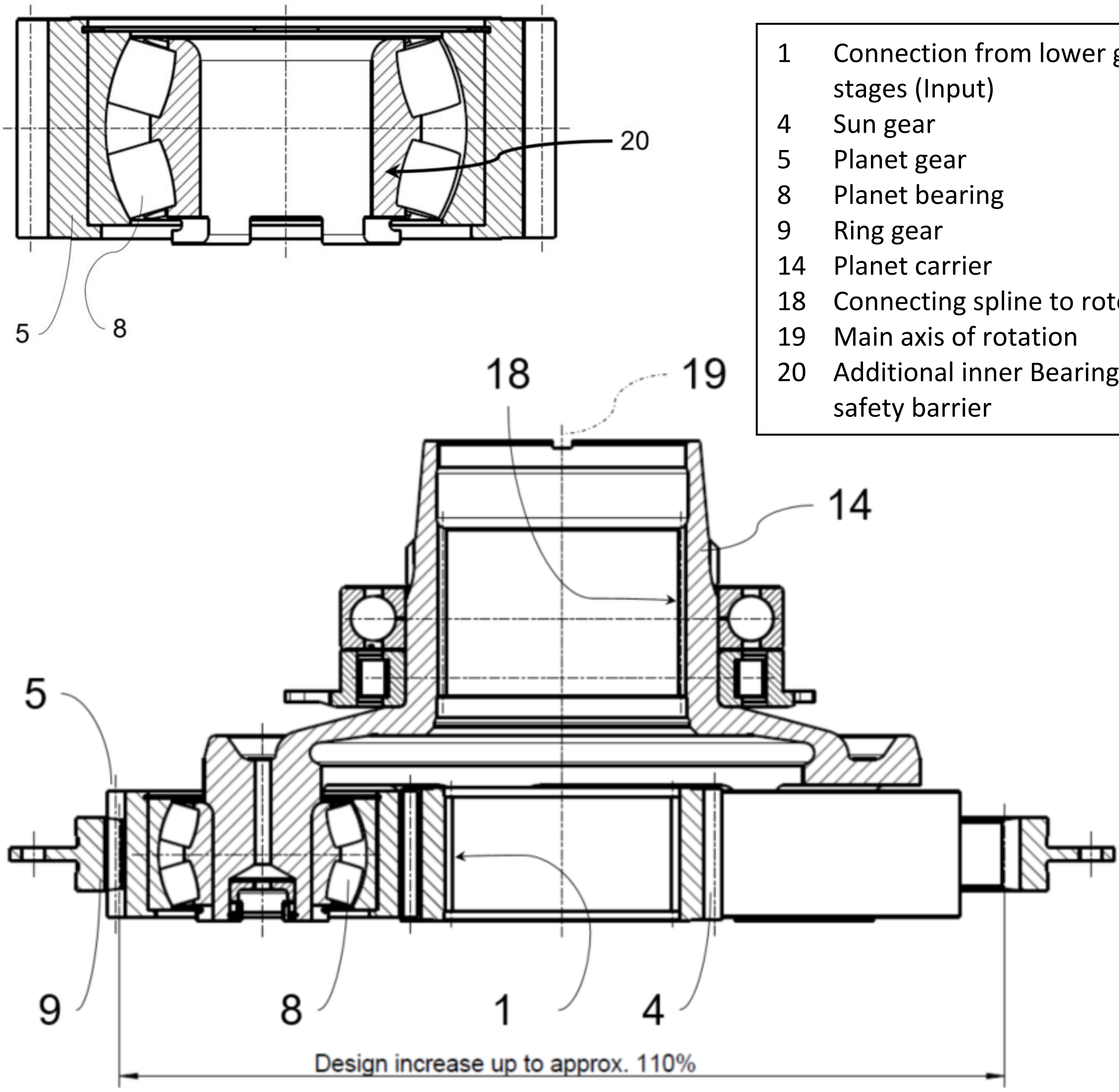
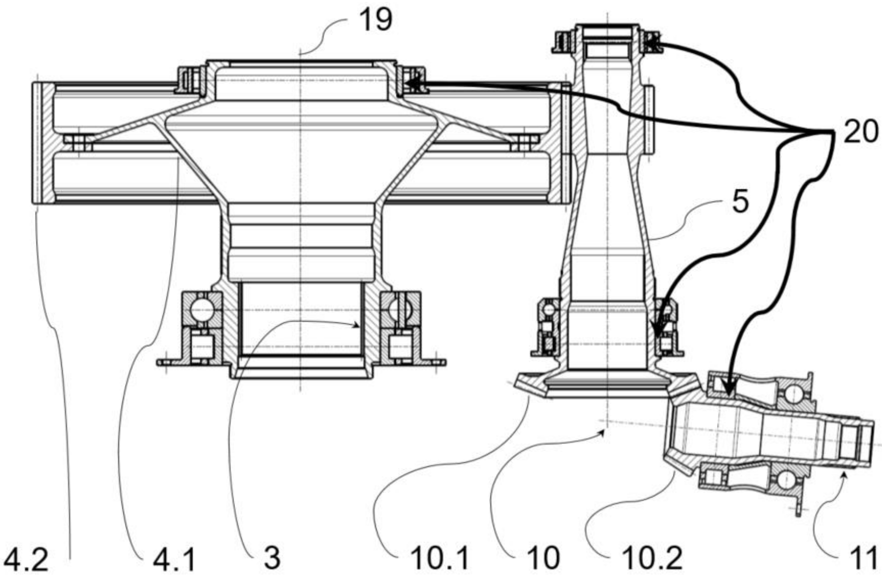


Figure 5: Alternative concept 4.1a (planetary stage, cage type carrier)



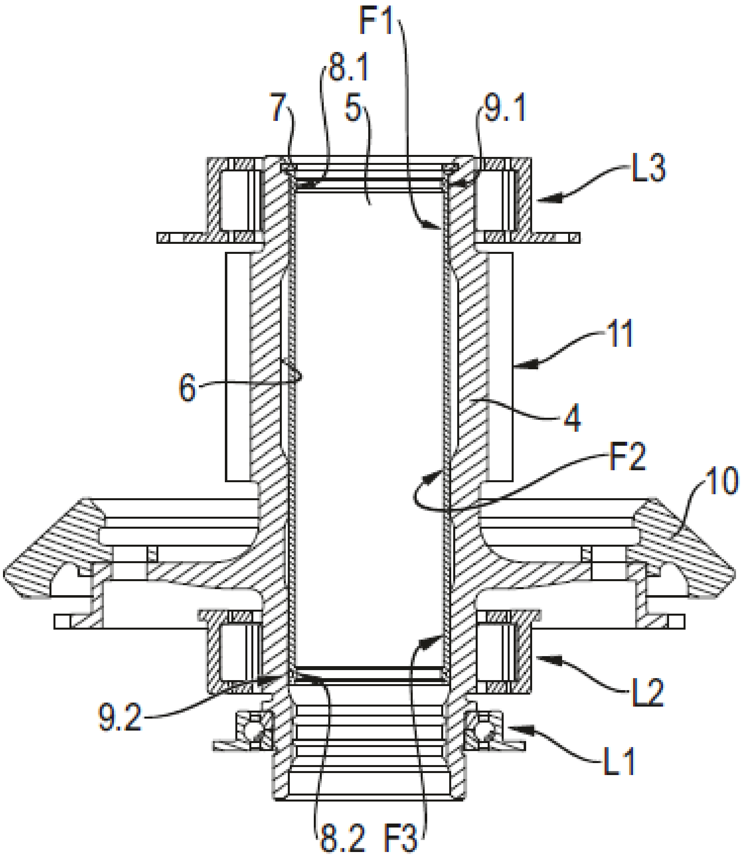
1	Connection from lower gear stages (Input)
4	Sun gear
5	Planet gear
8	Planet bearing
9	Ring gear
14	Planet carrier
18	Connecting spline to rotor shaft
19	Main axis of rotation
20	Additional inner Bearing ring as safety barrier

Figure 6: Alternative concept 4.1b (planetary stage, pin type carrier)



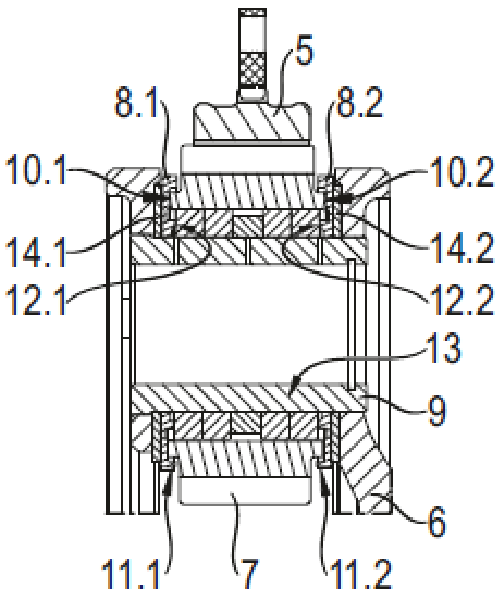
3	Connecting spline to main rotor shaft
4.1	Collector shaft
4.2	Collector gear
5	Gear
6	Shaft
10	Bevel gear stage
10.1/10.2	First/second bevel gear
11	Connecting spline to tail rotor drive shaft
19	Main axis of rotation
20	Additional inner bearing rings as safety barrier

Figure 7: Alternative concept 4.2 (collector stage)



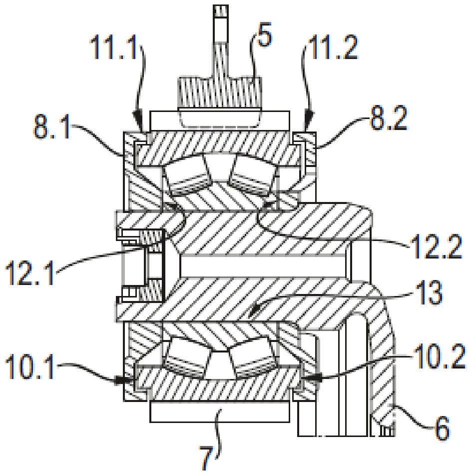
F1	First contact surface
F2	Second contact surface
F3	Third contact surface
L1	First bearing position
L2	Second bearing position
L3	Third bearing position
4	Hollow shaft
5	'Jamming preventer'
6	Inner surface
7	Snap ring
8.1	First groove
8.2	Second groove
9.1	First damping ring
9.2	Second damping ring
10	Bevel gear
11	Gear section

Figure 8: Alternative concept 5 (e.g. intermediate shaft)



5	Ring Gear
6	Planet carrier
7	Planet gear
8.1/8.2	First/second retaining ring
10.1/10.2	Bordure on planet gear
11.1/11.2	Bordure on retaining ring
12.1/12.2	Bordure on retaining ring
14.1/14.2	Shim

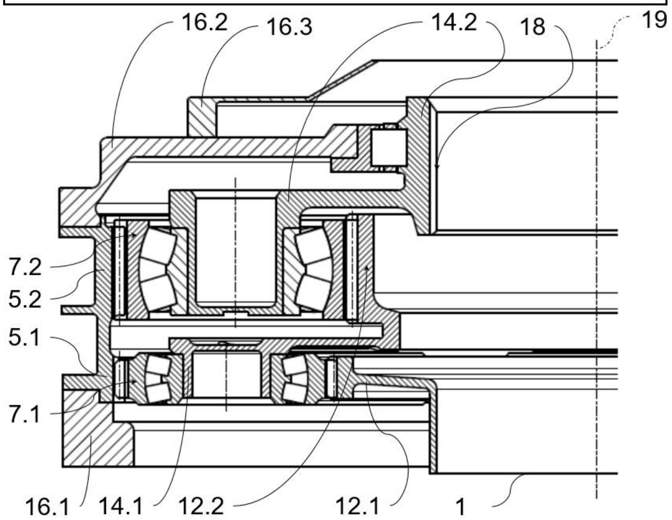
Figure 9: Alternative concept 6 (planetary stage, cage type carrier)



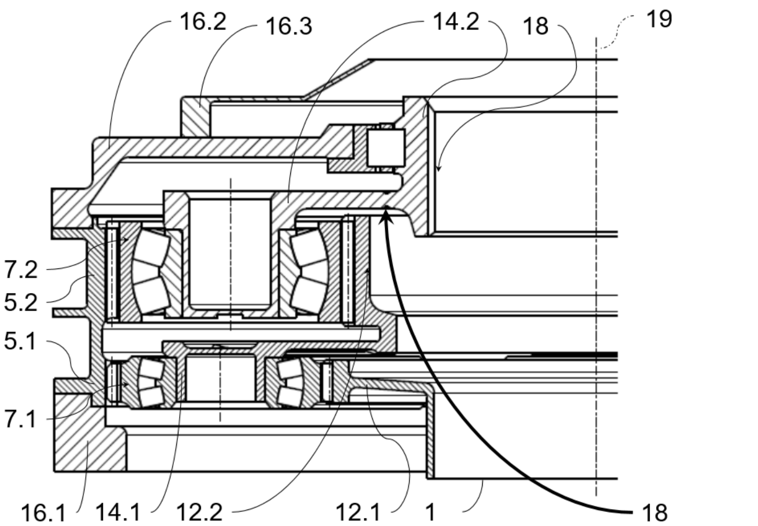
5	Ring gear
6	Planet carrier
7	Planet gear
8.1/8.2	First/second retaining ring
10.1/10.2	Bordure on planet gear
11.1/11.2	Bordure on retaining ring
12.1/12.2	Bordure on retaining ring
14.1/14.2	Shim

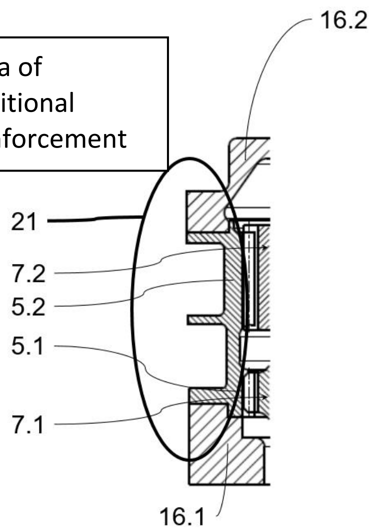
Figure 10: Alternative concept 6 (planetary stage, pin type carrier)

Solid planetary carrier, no fracture groove present



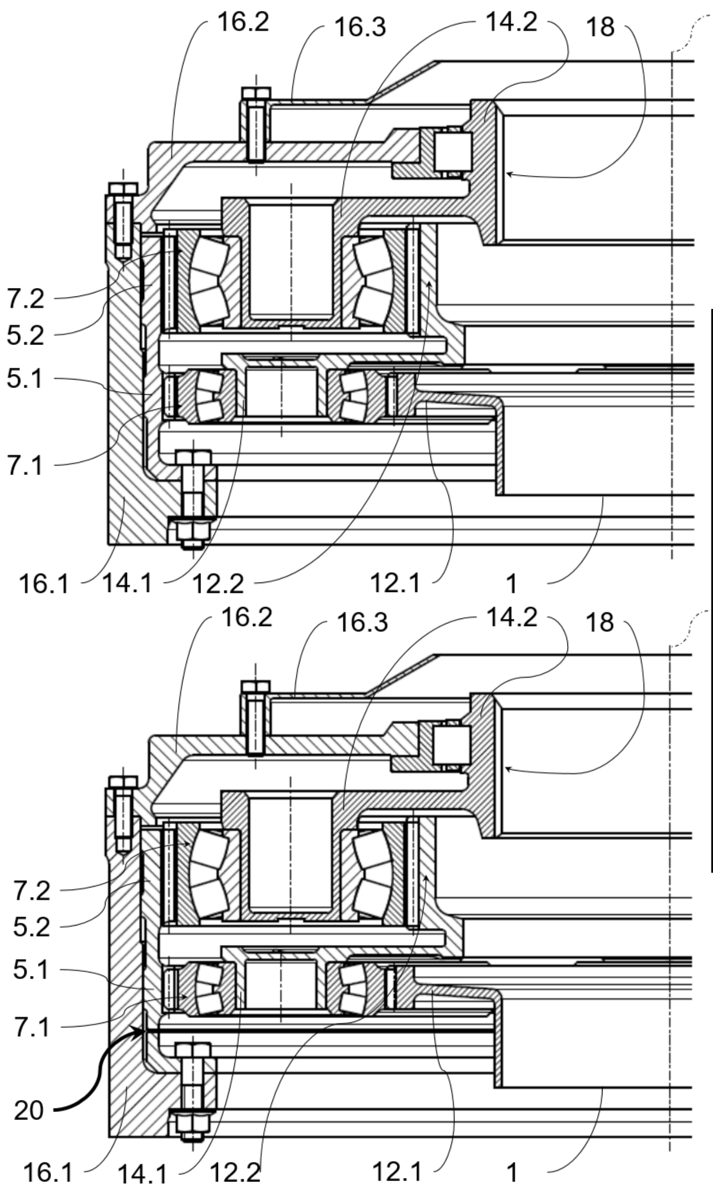
1	Connection from lower gear stages (Input)	
5.1	Ring gear (combined with 5.2)	
5.2	Ring gear (combined with 5.1)	
7.1	Planet gear	
7.2	Planet gear	
12.1	Sun gear	
12.2	Sun gear	(combined with 14.1)
14.1	Planet carrier	(combined with 12.2)
14.2	Planet carrier	
16.3	Cover	
16.2	Upper housing	
16.1	Lower housing	
18	Connecting spline to rotor shaft	
19	Main axis of rotation	
20	Emergency break groove	
21	Arear of additional reinforcement	





Planetary carrier equipped with an emergency break groove

Figure 11: Difference between original and alternative concept 7a (planetary stages, cage type carrier)



1	Connection from lower gear stages (Input)	
5.1	Ring gear	(combined with 5.2)
5.2	Ring gear	(combined with 5.1)
7.1	Planet gear	
7.2	Planet gear	
12.1	Sun gear	
12.2	Sun gear	(combined with 14.1)
14.1	Planet carrier	(combined with 12.2)
14.2	Planet carrier	
16.3	Cover	
16.2	Upper housing	
16.1	Lower housing	
18	Connecting spline to rotor shaft	
19	Main axis of rotation	
20	Safety Fracture	

Figure 12: Alternative concept 7b (planetary stages, m is separated from housing)

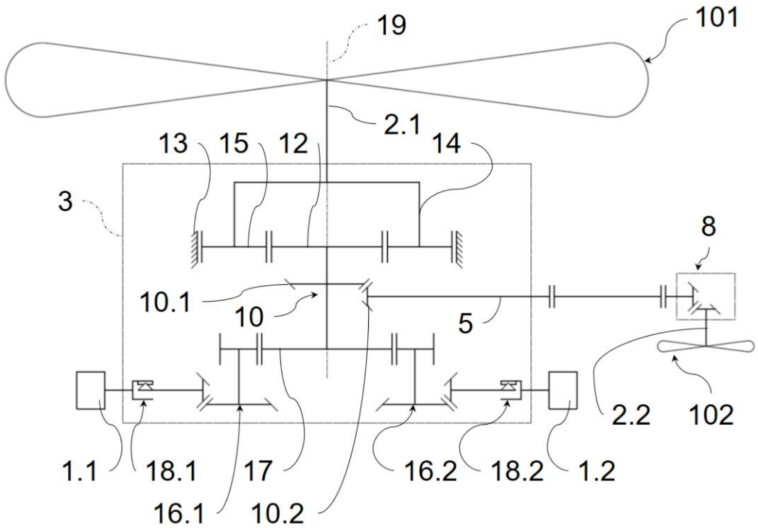
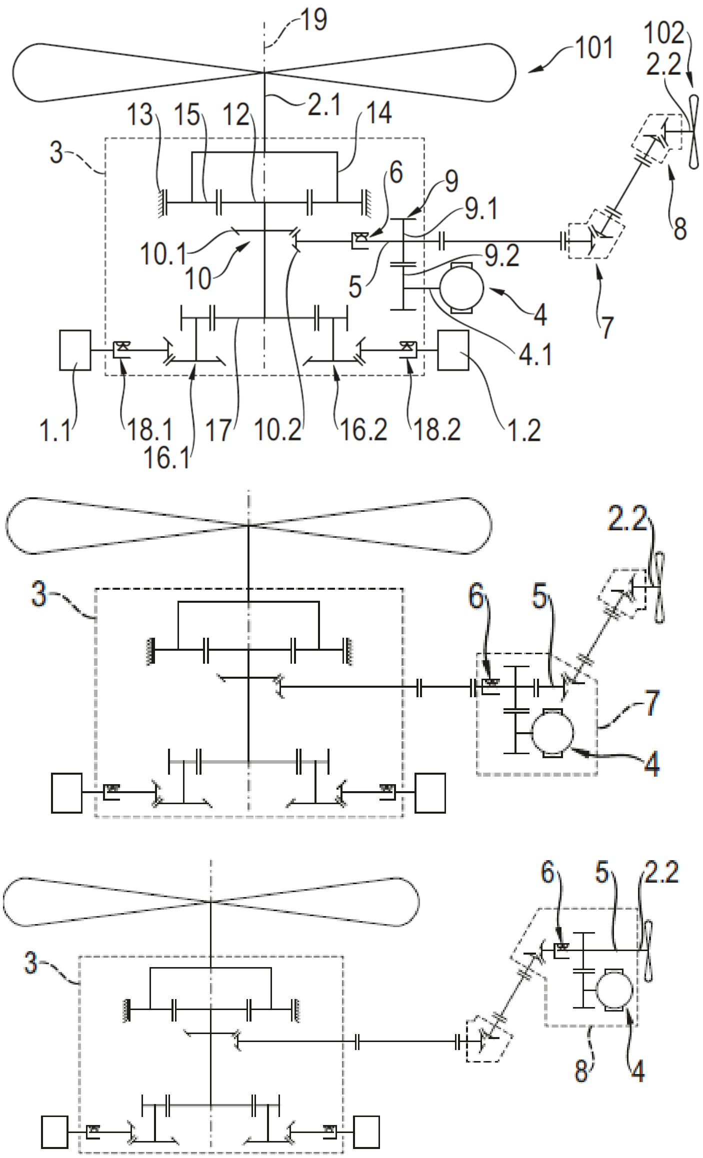


Figure 13: Alternative concept 8 (redundant power path)



1.1/1.2	Input stage
2.1/2.2	First/second rotor shaft
3	MGB
4	Electrical device
4.1	Rotor shaft of el. device
5	Shaft
6	Freewheel application
7	Intermediate gearbox
8	Tailrotor gearbox
9	Gear stage
9.1/9.2	First/second gear
10	Bevel gear stage
10.1/10.2	First/second bevel gear
12	Sun gear
13	Ring gear
14	Planet carrier
15	Planet gear
16.1/16.2	First/second collector stage
17	Collector gear
18.1/18.2	First/second freewheel
19	Main axis of rotation
101	Main rotor
102	Tail rotor

Figure 14: Alternative concept 9 (emergency drive)

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