# AN INNOVATIVE DISCONNECT DETECTION & OVERLOAD PREVENTION SUBSYSTEM FOR HIGHLIFT SYSTEMS

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ASES is the owner of patent DE 10 2019 114 463 B4, which has been granted by the DPMA in July 2023. The patent reserves the rights for the described technology.

**Keywords:** Actuation, Highlift System, Slat System, Flap System, Disconnect, Overload

**Abstract:**

Highlift systems for modern commercial aircrafts need, by authority regulations, provisions in order to ensure that flight safety is not affected due to disconnect and/or overload failures downstream the actuators, within the load path between the actuators, and the panels.

Disconnect Failures:
The considered disconnect failures may occur for example within the rack&pinion interface between the actuators and the panels of leading edge systems (“slat system”).
Special failures may occur within the slat actuators itself leading also to a disconnect of the driving part to a panel, whilst maintaining the drive through of the transmission – a so called “down-drive-disconnect”.
For both, flap and slat systems, disconnect detection subsystems are known and certified. Generally, the disconnect detection subsystems for the flap systems have been proven as very reliable for both kinds of panel support – track&carriage panel support and hinge-line support.

For the known slat systems the story appears different:
One of the two biggest aircraft manufacturers in the world uses subsystems for the slat system to detect disconnects – the other one does not. This is probably a direct result from the different attitudes of the FAA and the EASA concerning this topic. But is seems that this could be going to be changed in future due to harmonization ambitions of the authorities.

The known disconnect detection subsystems for the slat systems show a principally lower reliability compared to the flap side. One of the reasons for this is, that the aerodynamic loads on the slat panels vary very much more in dependence of aircraft operation cases (e.g. angle of attack) than the loads on the flap panels. This leads to difficulties for the adjustment of the functionalities in the monitoring electronics and for the adjustment of sensors. As a result, undetected disconnects or detections without disconnects (“nuisance trips”) can occur.

Overload Failures:
The considered overload failures may occur due to foreign objects, clamped elsewhere in the mechanical interface between the actuators and the panels. But also other occurrences, for example frozen grease due to water ingress in the actuators, may lead to a locked drive path and subsequent to high loads of the whole transmission path to this actuator.

Overload failures would lead therefore subsequently to damaged or ruptured aircraft structural parts as well as damaged or ruptured highlift system parts if no protection is in place.

The root cause of overloads as described cannot be fully avoided, but the damaging results. Most of the modern aircrafts are using so called station torque limiters. These are part of the actuators or located in special gear boxes near the actuators in the upstream transmission. Purpose of the station torque limiters is to stop the highlift system's operation (stop of rotating transmission) and to guide the high torque to special aircraft parts, which are designed to support these overloads. This scenario can be detected by special monitors (jam monitors), which subsequently commands the system into a fail-safe status.

This report gives an overview of an innovative Disconnect-Detection & Overload-Prevention Subsystem, which combines both: Disconnect detection and overload prevention. It replaces the already known disconnect detection subsystems as well as the station torque limiters and will probably lead to higher reliability and lower system weight.

The proposed Disconnect Detection & Overload Prevention Subsystem is based on the German patent DE 10 2019 114 463 B4, which has been granted by the DPMA in July 2023.

The invention is based on high reliable and precise angular position sensors (resolvers), which are used to measure the angular distortion of actuators between input and output shaft or gear boxes or combinations of gear boxes, transmission elements and actuators.

Angular distortion under load is a result from the "natural compliance" of these units. The compliance, for example of an actuator, is a function of its gear ratio and size.

This angular information is used in the monitoring electronics for failure detection in order to guide the highlift system into fail safe status and/or for annunciation of the pilot.

Due to above described special criticality of the slat system, this report concentrates on the slat system.

A comprehensive simulation model has been established in order to develop the two detection functionalities (overload monitor/disconnect monitor) in the control electronics.

The report ends with a principle reliability comparison of the proposed disconnect detection & overload prevention subsystem (DLDS) to a system with mechanical torque limiters and already used disconnect detection technology.

**Used Shortcuts:**

| | |
|---|---|
| A/C: | Aircraft |
| APPU: | Asymmetry Position Pick-Off Unit |
| C: | Control (Board or Functions) |
| DLDS: | Disconnect Detection & Overload Prevention Subsystem according DE 10 2019 114 463 B4 |
| DC: | Data Concentrator |
| DPMA: | Deutsches Patent und Markenamt |
| DSP: | Digital Signal Processor |

| | |
|---|---|
| D/N: | Droop Nose (GRA) |
| DOF: | Degree of Freedom |
| HLS: | Highlift System |
| I/B: | Inboard |
| ICI: | Interconnection Strut Interface |
| GRA: | Geared Rotary Actuator |
| EASA: | European Aviation Safety Agency |
| FAA: | Federal Aviation Authority |
| FSCL: | Flap/Slat Control Lever |
| FSECU: | Flap-Slat-Electronic-Control-Unit |
| LH-DC: | Left-Hand-Side Data Concentrator |
| LTLS: | Lower Torque Limiter Setting |
| M: | Monitoring (Board or Functions) |
| MCE: | Motor Control Electronic |
| MO: | Maximum Operation (Torque or Load) |
| PDU: | Power-Drive-Unit |
| POB: | Power-Off-Brake |
| PPU: | Position-Pick-Off-Unit |
| RDC: | Resolver-to-Digital-Conversion |
| RH-DC: | Right-Hand-Side Data Concentrator |
| RI: | Resolver Interface |
| SSA: | System Safety Assessment |
| STL: | System-Torque-Limiter |
| TRL: | Technologie Readiness Level |
| TSU: | Torque-Sensing-Unit |
| T/L: | (Station) Torque-Limiter |
| UTLS: | Upper Torque Limiter Setting |
| w/o: | without |

**Used Formula Signs:**

| | |
|---|---|
| f1, $f1_{obs}$, f2 : | Angular Measurements |
| $\phi$: | Rotational position |
| $\phi$1-1: | Rotational position 1 (input resolver) for GRA1 |
| $\phi$1-2: | Rotational position 2 (output resolver) for GRA1 |
| $\Delta\phi$: | Distortion of GRA between two measurement points |
| $\|\Delta\phi\|$: | Absolute value of distortion |
| $\|\Delta\phi_F\|$: | Filtered absolute value of distortion |
| der$\|\Delta\phi\|$: | Derivative of absolute value of distortion |
| $\|\Delta\phi 1\|$: | Absolute value of distortion of GRA 1 |
| $F_A$: | Airload |
| i: | Gear Ratio |
| KP: | Proportional gain of controller |
| KI: | Integrational gain of controller |
| $T_{in}$: | Input torque (in GRA) |
| $T_{out}$: | Generally for output torque (of GRA) |
| $T_{out1,2}$: | Output torques of GRA1 or GRA2 |
| $T^*_{out2}$: | Output torque sum of GRA2 |
| $T_{bd}$: | Torque of GRA1 which is needed to operate GRA from output side |
| $T_{pdu}$: | Torque at PDU output shaft |
| th: | Threshold of monitors |
| n: | Transmission speed |
| $n_{in}$: | Input speed of GRA (equals transmission speed) |
| $n_{out}$: | Output speed of GRA (Pinion) |

## 1. HIGHLIFT SYSTEM INTRODUCTION

The intention of this chapter is, to give a rough overview of HLSs as they are used on large commercial A/Cs. The understanding of the principal functions of the units and components of these HLSs is important for the understanding of the system functions and therefore, in a next step, important to understand the proposed DLDS.

By looking on the HLSs of the two biggest A/C manufacturers in the world, one can distinguish between two principal system designs. It would exceed this article by far to go into detail of all HLSs. Therefore the following description concentrates on the “European Style” of these systems. With some reservations, the statements are also valid for the “North American Style”, hence the proposed DLDS could be used on a wide variety of HLSs.

Figure 1-1 shows the scheme of a modern HLS with its units and components. The subsequent explanations are tailored to the most important details which are needed to understand the proposed DLDS. The scheme has no direct reference to a HLS of any existing A/C but takes advantage of modern technologies.

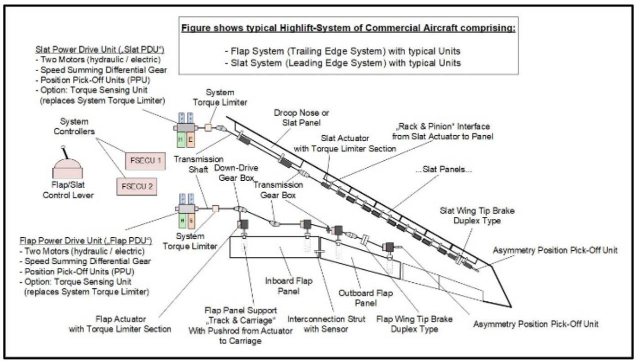


Figure 1-1, Decomposition of a HLS

**Power-Drive-Units:**

Two PDUs are used to operate the slat and the flap systems on the pilots demand. Two motors are used per PDU to convert the A/C hydraulic or electric power to mechanical rotational power. The mix of the type of the motors for a dedicated PDU depends on the A/C power distribution philosophy, costs and weight considerations. The scheme shows a more modern hydraulic-electric mix (1H1E), but all other combinations, for example 2H or 2E, are conceivable.

The motors are connected to a speed-summing differential gear, which converts motor speed and torque to the needed speed and torque on transmission level. If one motor fails to operate, the other one is able to operate the system with half speed.

The PDU is equipped with position sensors and possibly with pressure sensors in case of use of hydraulic motors.

The PDU may be equipped with torque sensing unit (TSU) at its mechanical output to the transmission. This TSU with its implemented functions in the FSECUs is the modern version of the mechanical system torque limiter (STL) and replaces it with some weight saving advantage. TSU or STL are used to protect the transmission and its elements against high torques in case of a jam somewhere in the transmission routing from the PDU to the actuators. The torque capability of the PDU must be sufficient for both wings. In case of a jam, this torque would be guided into one wing. It leads to weight savings of HLS units and structural parts of the wing, if this is prevented for example by the TSU.

**Flap-Slat-Electronic-Control-Unit:**

The FSECUs contain the following two principle function levels:

- Highlift system functions
- Motor drive functions

On both levels, control as well as monitoring functions are implemented.

The pilots input from the FSCL commands the FSECUs to operate the PDUs and therefore the HLS. System and motor monitors ensure protection against malfunction and failure cases. The latter on the dedicated motor drive level, hence in case of a failure just the affected motor-drive-lane will be arrested. The other one remains operable – this increases the availability of the HLS.

In one of the following chapters a more detailed view on the architecture of typical FSECUs is given, as well as a view on a proposed implementation of the DLDS functions.

**Transmission**:

The transmission consists of several shafts, bearings, joints, and gear boxes to route the mechanical power of the PDU to the actuators.

At the most outer section of the transmission, position sensors are installed. They are used as input for control and, very important, monitoring functions.

**Wing-Tip-Brake:**

WTBs are used for safety reasons: They are usually located between the two most outside actuators of the slat or the flap system. They arrest the transmission in case of typical transmission failures for example in case of a transmission rupture (disconnect of transmission parts). But the use of the WTBs is not limited to transmission failures.

**Flap-Actuators:**

For the most modern commercial A/Cs, rotary type actuators are used to operate the flap panels via a pushrod. For safety reasons, each panel is operated by at least two actuators (dual load path).

The input torque of each actuator is limited by a station torque limiter (T/L), hence they limit the output torque of the actuator in case of a jam within the load path from the actuator to the flap panel.

There are some possibilities to locate the T/Ls: They could be installed directly at the input shaft of an actuator or within a gear box upstream the actuators. Such gear boxes are anyway necessary, especially in a flap system in order to branch the main transmission to the actuators. Usually, the actuators of a flap system can't be installed directly in the main transmission.

In any installation cases, a well proven mechanical design is used for the T/Ls. The T/Ls performance plays an important role for the design loads of the actuators itself and, also important, for the sizing loads of the structural A/C parts. The maximum torques resulting from the T/Ls performance defines the important strength case "Limit Load".

The intention of the DLDS is to replace these mechanical T/Ls by electronic monitoring.

**Slat-Actuators:**

As for the flap actuator types, the same applies for the slat actuators: Modern commercial A/Cs take advantage of rotary type actuators (GRA). As shown in Fig. 1-1 two actuators operate one slat  panel via the so called mechanical rack&pinion interface and in case of a droop nose panel via a linkage. A drive-through-shaft enables that the actuators can be installed directly in the transmission line.

Since the GRAs are one of the focal points in this report, some information regarding the history of this important unit is given:

The design principles of the "GRA with through shaft" were first developed by the US company Western Gear and introduced first time at the B757 by another US company. These design principles were took over end of the 80th by equipment suppliers in UK and Germany for the A320 first time. The design offers a better aerodynamic of the airflow through the gap between the slat panel and the wing body, due to the rack&pinion interface.

The invention of the GRA design principles constitute a big step in the development of commercial A/Cs. This type of slat actuators are nowadays used in most of the commercial A/C types.

The technology described in this report with the suggested improvements for the slat actuation GRAs are the next step of evolution.

A GRA is divided principally into two sections: A torque limiter section and a gear section. The branch-off ("down-drive") from the through-drive shaft to the gear section and further to the rack&pinion interface runs over the T/L The T/L limits the output torque to the rack&pinion interface and protects therefore the A/C structural parts. Again, as for the flap actuators, the performance of the T/L plays an important role for the design loads of the actuator itself and for A/C structural parts.

As for the flap system, the intention of the DLDS is to replace the mechanical T/Ls by electronic monitoring. The proposed DLDS should be able to achieve identical or better performance.

Since this report concentrates on a DLDS which is installed in a slat system, some more details are given in the following figures 1-2 and 1-3.

Fig. 1-2 shows some details of the Rack&Pinion and installation details as well as some details of the GRA.

Fig. 1-3 shows the principle performance scheme of a mechanical T/L of a GRA. The performance bandwidth of the GRA is defined by two curves – one curve is based on high drag torques and low gear efficiency (“low performance curve”) and the high performance curve which is defined by low drag torques and high gear efficiency. In addition, tolerances for the T/L must be considered.

The T/L should be adjusted to transfer the maximum operation torque (MO) at the output of the GRA with some margin under consideration of the low performance curve of the GRA. No T/L lockout must occur! This adjustment is referenced as LTLS.

By taking into account the T/Ls tolerances, this leads, by using the high performance curve of the GRA, in case of a T/L lockout to a load case called UTLS.

It is the intention of the A/C manufacturer stress engineers to keep the relationship UTLS/MO as low as possible. This relationship defines the limit load level of structural parts (rack&pinion interface, panel, etc.) and is therefore a highly weight sensitive engineering number!

Clearly, that it must be the intention to keep this relationship also as low as possible with the introduction of the DLDS.

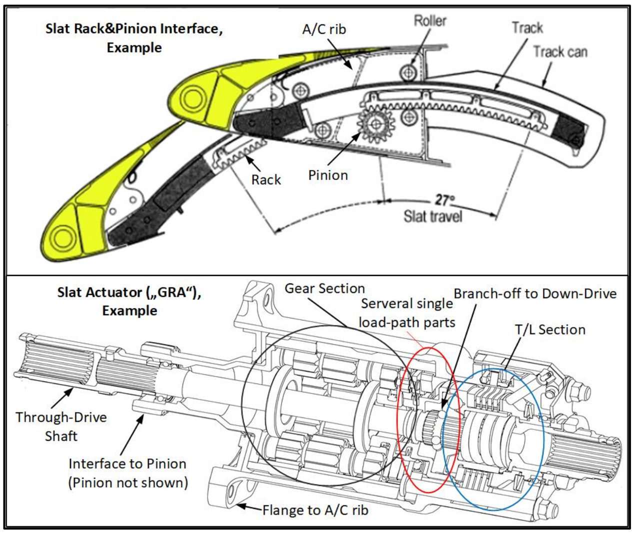


Figure 1-2, Slat Panel and Rack&Pinion Interface, Slat Actuator Sections

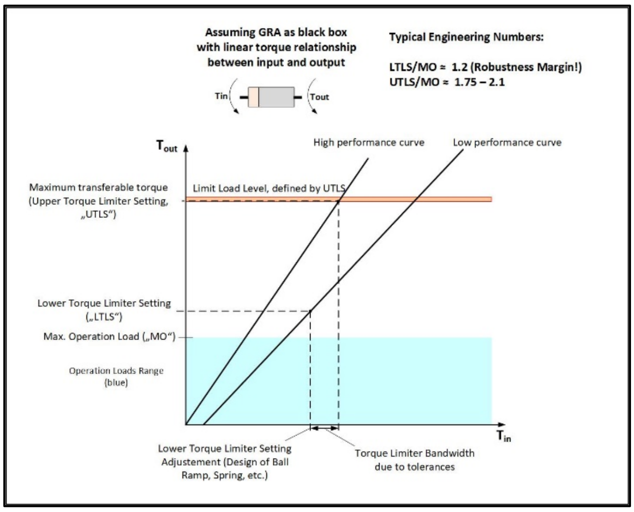


Figure 1-3, Principle T/L Performance of GRA

## 2. DISCONNECT PROBLEM

As mentioned, this report concentrates on an application of the DLDS for the slat system, hence, the following disconnect descriptions are referred to this subsystem of the HLS.

The disconnect problem can be divided into the two principle problems:

- **Case A:** Disconnects in the load path from the GRA branch-off to the down-drive over the gear section to the pinion.
  Since there are single load path parts in the GRA design from the point of the branch-off to the gear section (refer to Fig. 1-2), in case of a rupture of one of these single load path parts, the following problem will occur:

  The side of the panel where a rupture inside the GRA occurs is no longer operated by this GRA. But the trough-drive is still intact and all other GRAs will be operated by the transmission. Therefore the panel will be operated by the remaining intact GRA alone and the gear section of a failed GRA is operated from the pinion side (output side) by the intact GRA over the slat panel. This will induce high loads on the structural parts since the back-driving efficiency of the gear section of the failed GRA is low (details will be given later in the text). Useless to say, that such a scenario will increase the loads on the intact GRA also considerably.

Such disconnects are called “**Down-Drive-Disconnect-Whilst-Through-Drive-Maintained**”.

- **Case B**: Disconnect in the load path from the actuator output to the panel: Both GRAs are intact, but the one at the side, where the disconnect happened, is more or less not loaded with the aerodynamic loads from the rack&pinion interface.
  Such disconnects are called **“Free-Wheeling-Disconnect”.**

The figures 2-1 and 2-2 show the two principle cases:

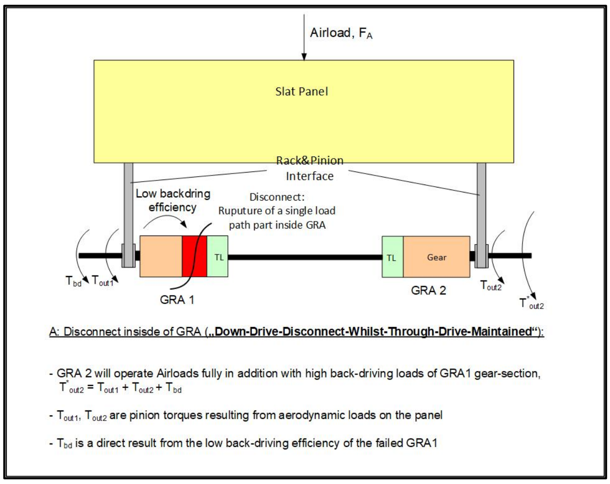


Figure 2-1, Case A: Down-Drive-Disconnect-Whilst-Through-Drive-Maintained

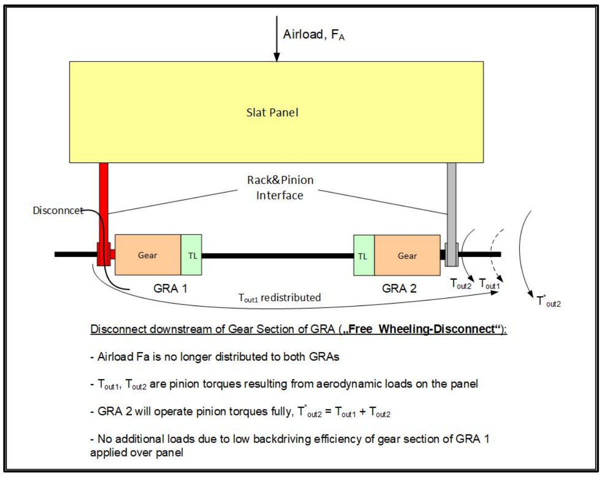


Figure 2-2, Case B: Free Wheeling Disconnect

From figures 2-1 and 2-2 the hazard of case A can be clearly seen: The drastically increased loads of the intact GRA 2 resulting from the low back-driving efficiency of the gear section of the failed GRA 1.

This could lead to a subsequent disconnect on the intact side also – probably due an accelerated fatigue problem.

Hence, considering case A, a <u>single</u> load path disconnect could results very quick in a <u>dual</u> load path disconnect!

Looking on some overall engineering numbers:
The efficiencies, measured from the T/L section to the actuator output, for the normal operation case of a GRA range from approx. 0.5 – 0.8.
In case of an opposite operation, when the gear stage is operated from the actuators output side, the back-driving efficiency drops due to the planetary gear arrangement to approx. 0 – 0.2.

Further questions will come up after such considerations:

1. Does the T/L of the intact GRA 2 locks-out in case A or case B?
2. Does case B lead to a skewed slat panel? Case A probably will.

Regarding question 1: To use a T/L lock-out as indication for a disconnect is not a reliable indication and therefore un-safe. The reason is that the T/L adjustment includes aerodynamic load margins and further margins for the GRA performance variation over the temperature range, refer to Fig. 1-3. The logic behind a T/L adjustment is, that it must lock-out in case of a “hard” jam, but shall robust enough to cover all kind of operation cases of the A/C, for example cold/wet weather conditions. If such a T/L adjustment logic is not in place, a un-reliable slat system would be the result!

Regarding question 2: This depends on the structural stiffness of the panel and the rack&pinion interface. To use the panel skew as an indication for a disconnect seems therefore not reliable.

Fig. 2-3 gives an overview regarding the principle possibilities to cover specially case A. For example, a disconnect-detection system could be principally replaced by a more expensive GRA design leading to a “safe life” design. This possibility has been chosen for the latest development of the European A/C manufacturer.

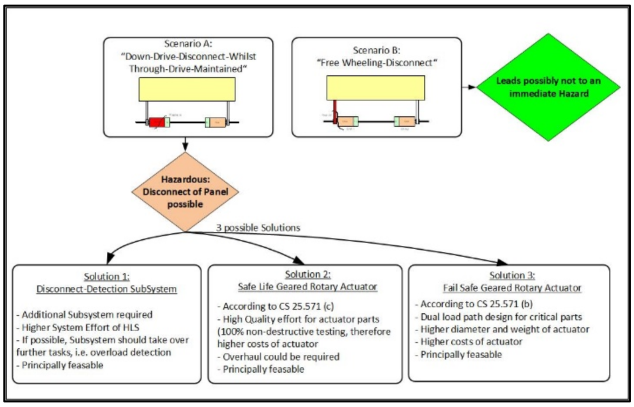


Figure 2-3, General Overview regarding possibilities to cover Down-Drive-Disconnect-Whilst-Through-Drive-Maintained

## 3. EXISTING TECHNOLOGIES FOR DISCONNECT DETECTION

The following is intended to give a brief overview of the existing technologies in order to detect disconnects.
Sometimes these subsystems are labelled "skew-detection-system" and this needs some clarification: A loss of a load path ("disconnect") **may** lead to a skewed panel but this is not a logical must (as explained in the previous chapter)!
High structural stiffness in addition with a special location of the disconnect can avoid a skew after the disconnect, hence the disconnect may remain un-detected!.

Skew detection subsystem using way or position measurement for detection.

But a disconnect leads in all cases to an alteration of the loads of the affected GRA and/or on the mechanical interface to the panel.

Consequently, disconnect detection subsystems which are using load measurement appear more reliable in order to detect the total volume of failure cases.

Based on the above, disconnect detection subsystems can be divided principally in way (or position) measuring systems and in load measuring systems.

The following overview constitutes not an exhaustive list:

Way / Position measuring sub-systems:

- Lanyard types
- Draw wire types
- Cutting wire types
- Optical measurement types
- Multiple target types
- Interconnection strut sensor types

Load measuring sub-systems:

- Load pin types
- Torque sensor types

## 4. DISTORTION MEASUREMENT ACCORDING TO PATENT DE 10 2019 114 463 B4

Patent DE 10 2019 114 463 B4 reserves the idea to use the distortion of actuators, gear boxes and shafts under load as signal for a monitoring system in order to detect disconnects and prevent overloads.

Looking on some overall engineering numbers:
The input stiffness of typical slat GRAs of commercial A/C ranging from 0.5 – 1.8 Nm/rad.
Using a mean stiffness of 1.5 Nm/rad, every 100 Nm of load on the GRA output (pinion) would lead to a distortion of ≈10° without considering the efficiency.
The example is intended to demonstrate that there is enough signal "bandwidth" available for use in a monitoring system. The exact distortion must be evaluated by test results.

Figure 3-1 shows the principles of the design to measure the distortion of a GRA under load: Two resolvers with solid rotors are integrated in the GRA. The input-resolver measures the angular movement of the input shaft at the branch-off to the down-drive. The output-resolver measures the angular movement of the pinion.

The parts of the T/L are deleted as well as the sealing between the gear section and the T/L

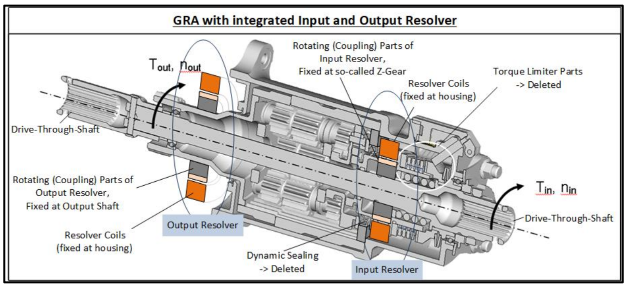


Figure 3-1, GRA with integrated Resolver

From the design in Fig. 3-1, two simplified lumped mass models of the GRA can be established for better understanding. Based on them, a formula for the distortion $\Delta\phi$ of a GRA can be derived, refer to Fig. 3-2.

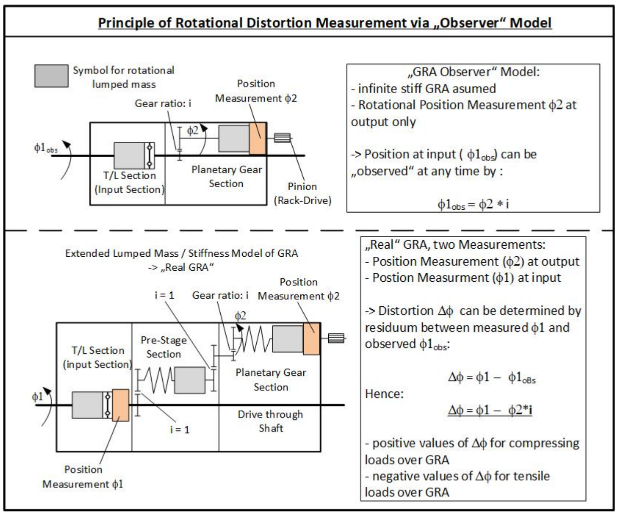


Figure 3-2, Lumped Mass GRA Models with "Observer" Model

Clearly, resolvers with high precision and reliability shall be used. On the market available are single-pole and multi-pole types where the latter feature a higher precision. The typical numbers for the angular position errors of highly precise resolvers with solid rotor are:

- Single-pole type: error ≈ 1°
- Multi-pole type: error ≈ 0.1 ° (depending on the number of poles)

The resolvers are connected by 3 signal lines to the interface of the DC (refer to next chapters): sine-signal, cosine-signal and excitation.

Interface boards with well proved standards of the Aerospace Industrie such as RDC or DSP can be used.

It appears logic that the $2\pi$ jumps, which occur one time per a rotation for the single-pole types or multiple times for the multiple pole types, must be removed before evaluating the distortion according to Fig. 3-2. The jumps must be counted.

## 5. MONITORING

Two monitors have been developed in order to detect disconnects and overload. The development of the monitors is based on investigation with the simulation model, which is explained in the next chapter.

Case A and B, as explained in chapter 2, have been used with the assumption that they lead to an abrupt loss of the load path. This is in fact a theoretical case and leads to open questions, for example what happens in case of a slow disconnect caused by a long term crack propagation? Such questions can not be answered in this report.

Overload modelling has been used with the assumption that the slat panel is blocked by foreign object, leading to a hard jam.

Figure 4-1 shows the two monitors:

For the disconnect detection, the derivative of the absolute value of the distortion is used as the input signal into the disconnect monitor.
Low pass filtering of der(|$\Delta\phi$|) is advisable and/or a DT1-function for the derivation task.

For overload detection, simply the absolute value of the distortion is used.

As shown in figure 6-1, the monitors have the authority over the motor and POB control of the PDU. In case of a detected failure, 0 rpm speed is commanded and the POBs will arrest the transmission but also the WTBs could be used to stop the transmission.

The resolvers and the excitation network(s) of them can be monitored with the already well proven monitors in order to detect failures of the coils or of the excitation network:

- Open/short circuit monitors in order to detect failures of the resolver coils

- ($sine^2 + cosine^2 = 1$) - monitors in order to detect excitation failures

Therefore a high reliable sensor arrangement can be achieved.

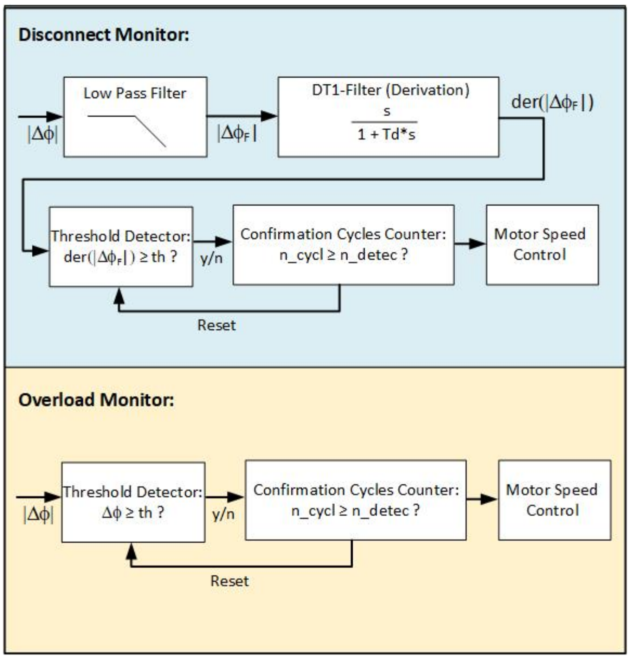


Figure 4-1, Monitors

## 6. ELECTRONIC ARCHITECTURE OF DLDS

An electronic architecture, which is shown in figure 5-1, is proposed. Note that it shows the flap disconnect monitoring with an interconnection strut also, but this topic will be not drawn further (as already remarked).

The figure suggests that data concentrators (LH-DC, RH-DC) are used for each side of the wing. The installation of the DCs will be, as a weight saving measure, somewhere in the middle sections of both wings and the signal line to the FSECUs comprises the monitoring status of all GRAs per wing side.

The tasks of the DCs are:

- Constitute the interface for each GRA resolvers.
- Evaluate the derivative of the distortion der|Δϕ| for each GRA.
- Monitoring of disconnect according to Fig. 4-1 for each GRA.
- Evaluate the distortion |Δϕ| for each GRA.
- Monitoring of overload according to Fig. 4-1 for each GRA.
- Monitoring of resolver monitors open/short circuit, excitation.
- Hand over the monitoring status to FSECUs.

Further, figure 5-1 is based on the following assumptions:

- It is not necessary to use duplex type of resolvers.
- It is not necessary to duplicate the data concentrators per wing side.
- The data concentrators are connected to the FSECUs either by a direct status wire (dashed line) or via A/C Bus.
- In case of a disconnect or overload failure for example on the right wing side, slat channel 2 would re-act with appropriate command of the electric motor and POB for the slat PDU and hand over the failure status via the cross communication to FSECU 1 / slat channel 1 in order to command the hydraulic motor accordingly.

The proposed DLDS constitutes therefore a simplex architecture and this induces clearly questions regarding reliability and safety. They must be answered by establishing a detailed SSA by the A/C manufacturers with respect to authority requirements.

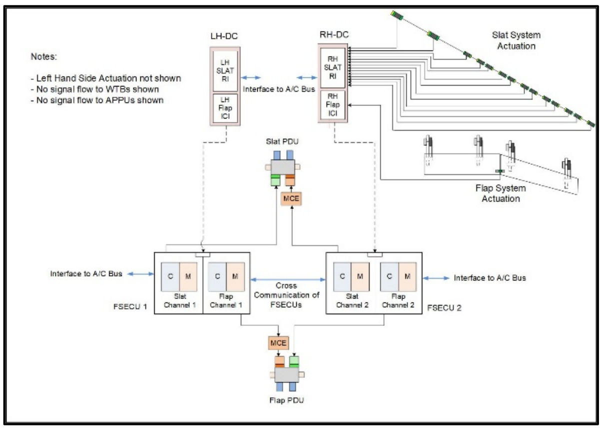


Figure 5-1, Electronic Architecture and Signal Flow

**System variant in order to reduce number of sensors:**

A possible system variant with the aim to reduce the number of resolvers could be established by:

- Deletion of the input resolvers of the individual GRAs.

- Placement of x transmission resolvers at convenient locations within the transmission line.

It must be investigated what reduction of the total number of GRA input resolvers to x transmission sensors is possible. Such a reduction will clearly lead to an additional error of the calculated distortion, since the compliance of the transmission from the location of a transmission resolver to a dedicated GRA will be included in the measurement.

On the other hand, some of the transmission resolvers could possibly contribute to other HLS system functions, for example transmission overspeed sensing.

## 7. PROOF-OF-CONCEPT BY SIMULATION

**Model Description:**

A comprehensive simulation model based on Matlab/Simulink has been established in order to investigate the principle behavior of the slat system during disconnect and overload failures and to develop the monitors.

The model is composed by the two principle sub-models:

- Sub-model A: Model of simplified PDU with control and monitor functions, refer to figure 6-1.
- Sub-model B: Model of one slat panel with GRAs and shafts, refer to figure 6-2.

The two GRA models are principally composed as shown in the lower part of figure 3-2.

Due to the use of Simulink S-Functions with implemented dedicated functions specially for this type of aerospace simulations, the spring stiffnesses can be altered during the running simulation, for example set to 0. This is necessary for the failure introduction in the model.

Table 6-1 shows the main data/parameters of the model:

| Data / Parameter | Value | Unit | Remark |
|---|---|---|---|
| Airload, $F_A$ | 3000 | N | Leads to a maximum load of each GRA of 400 Nm at the pinion (example!) |
| Transmission Speed, n | 1000 | rpm | |
| Ramp-up time of speed | 2 | s | By sequencer |
| GRA gear ratio, i | 200 | - | |
| GRA input compliance | 1.7 | Nm/rad | |
| GRA efficiency opposing load | 0.5 | - | |
| GRA efficiency aiding load | 0.1 | - | |
| PDU torque capacity factor | ≈ 2 | - | Approximately 50% of PDU power consumption under max. $F_A$ |
| Speed Control Frame Time (sample and hold) | 2 | ms | |
| Monitoring Frame Time (sample and hold) | 2 | ms | |
| Type of Speed Control: | PI | | |
| Overload Monitor Threshold, $\|\Delta\phi\|$ | 117 | ° | 5 confirmation cycles |
| Operation Shut-Down by Overload Monitor | By POB only | - | Monitor commands the POB to arrest the PDU motor(s) |
| Disconnect Monitor Threshold, der($\|\Delta\phi\|$) | 300 | °/s | 5 confirmation cycles |
| Operation Shut-Down by | By POB only | | Monitor commands the POB to arrest |

| Data / Parameter | Value | Unit | Remark |
|---|---|---|---|
| Disconnect Monitor | | | the PDU motor(s) |

Table 6-1, Simulation Data / Parameters

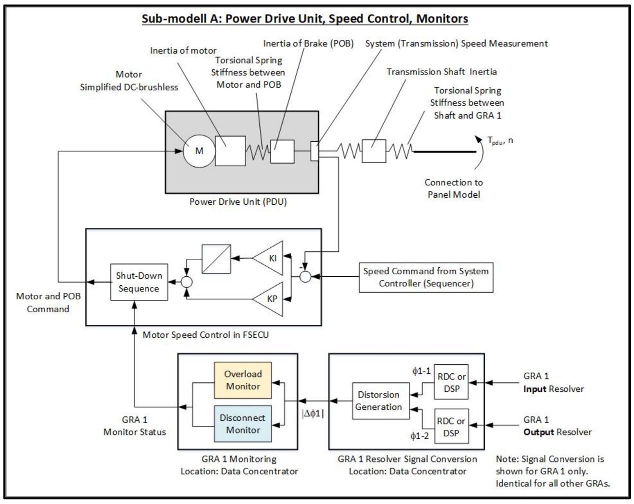


Figure 6-1, Sub-model A: PDU with control and monitor functions

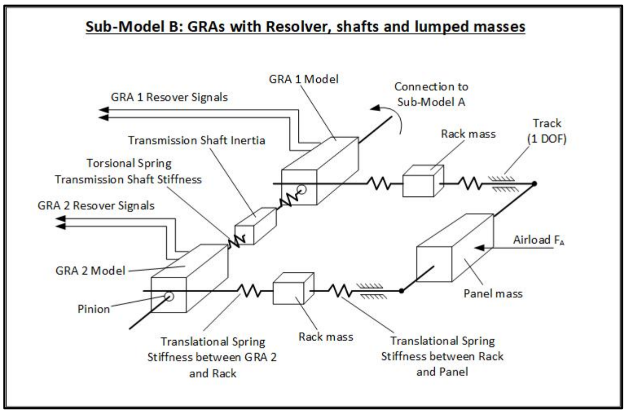


Figure 6-2, Sub-model B: Slat Panel with GRAs, shafts and lumped masses

### Simulation Cases Description:

The following three failure cases have been investigated:

1.) Overload due to jamming of rack 1 (foreign object), refer to Fig. 6.3.

2.) Disconnect Case B, refer to Fig. 6.4.

3.) Disconnect Case A, refer to Fig. 6.5.

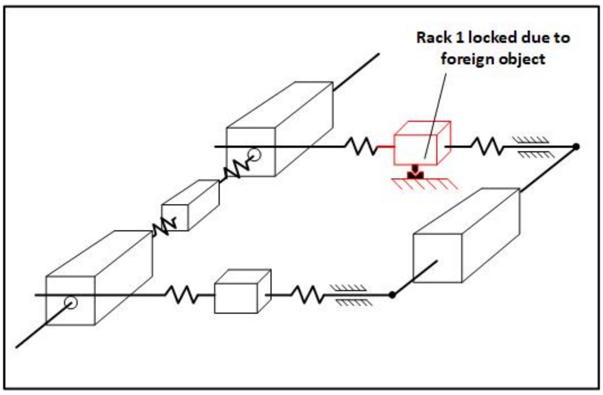


Figure 6-3, Jamming of rack1 in simulation model

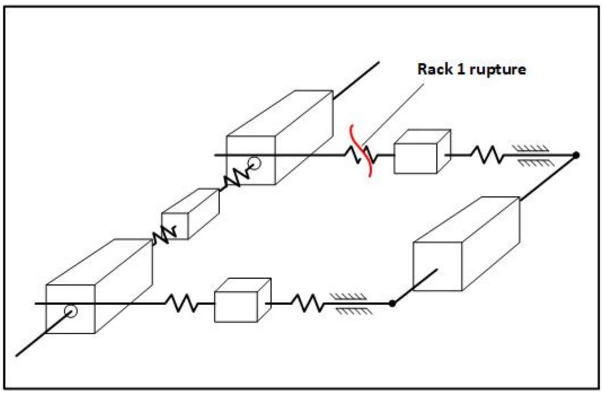


Figure 6-4, Disconnect Case B in simulation model

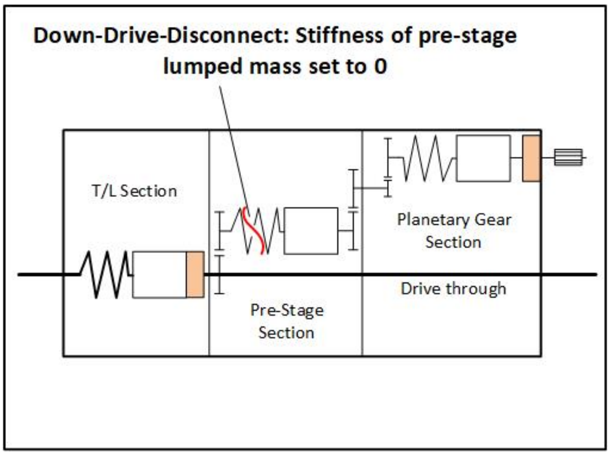


Figure 6-5, Disconnect Case A in simulation model

### Summary of Simulation Results:

It would exceed this report by far showing all details of the results. Instead of this, a summary is given in table 6-2.

| Simulation Case | Successful Failure Detection ? | Findings |
|---|---|---|
| 1 | yes | POB delay time is critical and will affect the jam loads. Reverse motor operation after overload detection could be needed. Relaxation procedure after stop of transmission speed could be needed. |
| 2 | yes | Interferences between overload monitor and disconnect monitor likely. Disconnect monitor timing could be probably relaxed, based on Authority requirements (detection within one operation cycle). |
| 3 | yes | Identical to simulation case 2. |

Table 6-2, Simulation Result Overview

So far, the results show, that the patent idea of measuring the distortion and the implemented monitoring concept is principle viable. The simulations showed, for a first step, promising results!

But clearly, much more investigations by simulations and by tests are needed to achieve a higher TRL.

## 8. RELIABILITY COMPARISON

The proposed DLDS comprises a high number of sensors and additional electronics. Therefore a principle analysis has been carried out in order to compare it against a slat system with conventional technology.

The basis of the used reliability numbers for the analysis is shown in Table 7-1. Only units are included in the analysis which are affected by the proposed DLDS and the two covered functions of overload prevention and disconnect detection.

For example, the PDUs are considered as identical for a HLS with or without a DLDS – consequently the PDUs are not included in the comparison.

The first row of Table 7-2 shows the number for a conventional slat system with GRAs which are equipped with conventional mechanical T/Ls but w/o disconnect detection subsystem.

A hypothetical MTBF number for a disconnect detection subsystem (for example lanyard type) is estimated (2nd row, red) in order to achieve an *identical reliability* as for the DLDS, which is shown in the 3rd row.

The red number in the 2nd row stands therefore as “budget” for a conventional disconnect detection technology in order to reach an identical reliability as the DLDS.

| Item | Functional MTBF [FH] | Remark |
|---|---|---|
| T/L of Slat or D/N GRA | 2.700.000 | - |
| Slat GRA w/o T/L | 9.800.000 | - |
| Slat D/N GRA w/o T/L | 2.000.000 | Refer to Fig. 2-1, D/N types used for the first I/B panel |
| Resolver (1off) | 8.000.000 | In-service figure from hydraulic motor application with severe vibration. |
| Connector | 100.000.000 | |
| DC (1off) | 74.000 | |
| Harness | 250.000.000 | Total Harness for one wing side |

Table 7-1, Reliability Figures for Analysis

| **Variant** | **MTBF [FH]** | **Comment** |
|---|---|---|
| Slat system with GRAs equipped with mechanical T/Ls - **w/o** disconnect detection subsystem | 67.000 | Overload prevention is covered only |
| Hypothetical Budget for a conventional disconnect detection subsystem | 42.500 | Disconnect detection is covered only |
| Slat system with DLDS | 26.000 | Overload prevention and disconnect detection covered |

Table 7-2, Result of Reliability Comparison

## 9. SUMMARY

The proposed Disconnect-Detection & Overload-Prevention-Subsystem according to Patent DE 10 2019 114 463 B4, which combines both – disconnect detection and overload prevention, can replace the already known disconnect detection subsystems as well as the mechanical station torque limiters.

The proposed design principles for mechanical units, electronics and monitor functions have been successfully evaluated.

It has been shown that the proposed DLDS is able to detect with a high reliability *both* considered disconnect cases A and B.

Also, overload can be detected with a high accuracy of the overload level.

The replacement of the conventional technologies by the DLDS can provide the following additional advantages:

1. The currently used grease for the GRA gears can be replaced by better lubricants such as Aeroshell 33 or Semifluid, a mixture of grease and oil. These lubricants show a significantly improve water assimilation capability than pure grease. In-service experience shows that frozen grease in a GRA leads to unwanted T/L lockouts. Hence, this advantage of the possibility to use better lubricants will improve the reliability of the slat system further!

2. It is expected that the critical relationship UTLS/MO can be reduced significantly compared to conventional T/L. The will result in weight savings.

3. Clear indication of the location (affected GRA) of an overload case. This will reduce the maintenance effort.

4. The proposed resolvers can continuously be monitored by the DCs. Therefore possible dormant failures can be avoided.

5. The monitors for the two functions are flexible and can be adapted to special A/C needs. Further development for example long term “health monitoring” is possible.

Last but not least, the proposed DLDS shows potential for further simplifications and improvement by taking over other HLS system functions for example transmission overspeed detection.

## Attachment: Figures

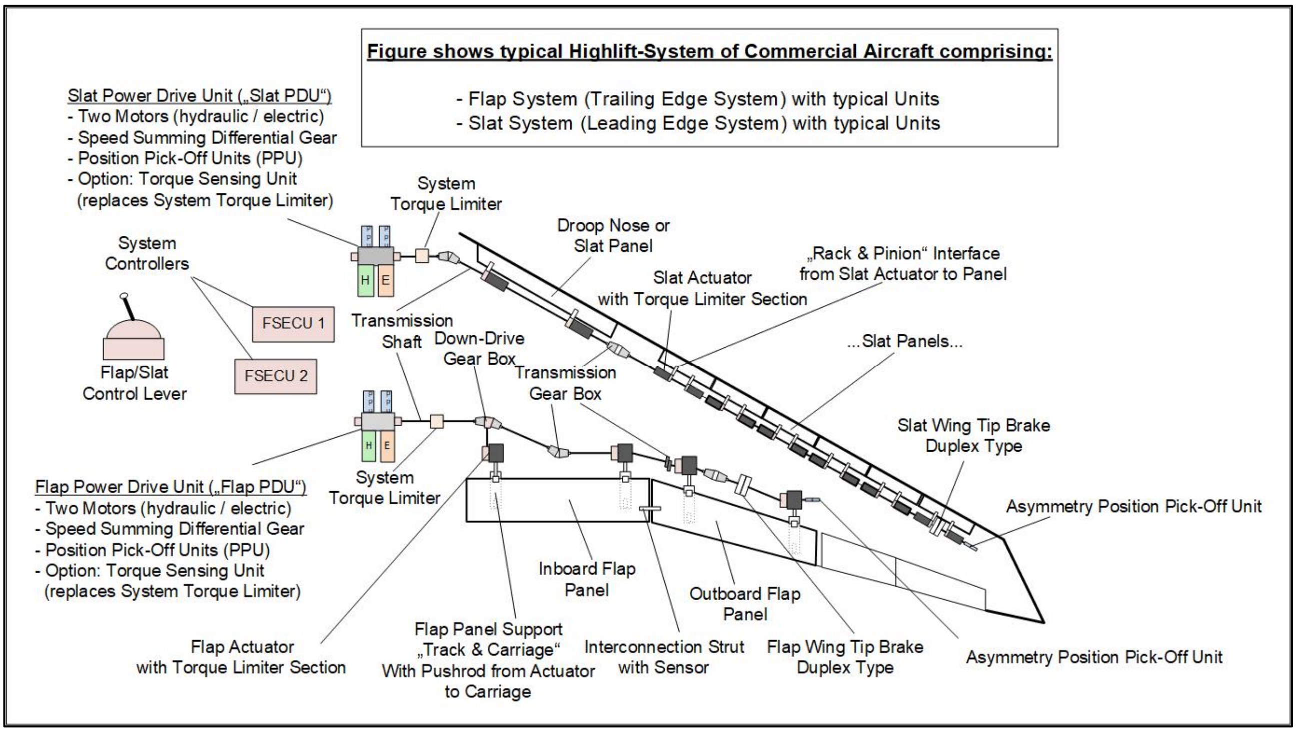


Figure 1-1

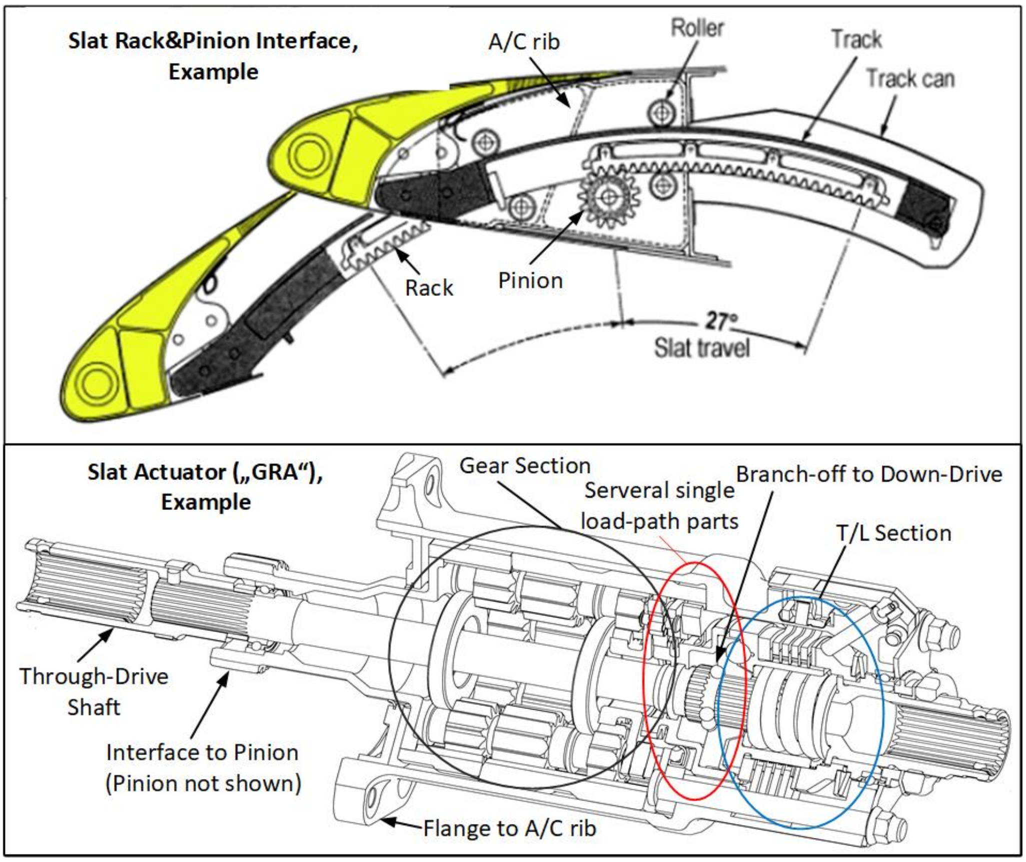


Figure 1-2

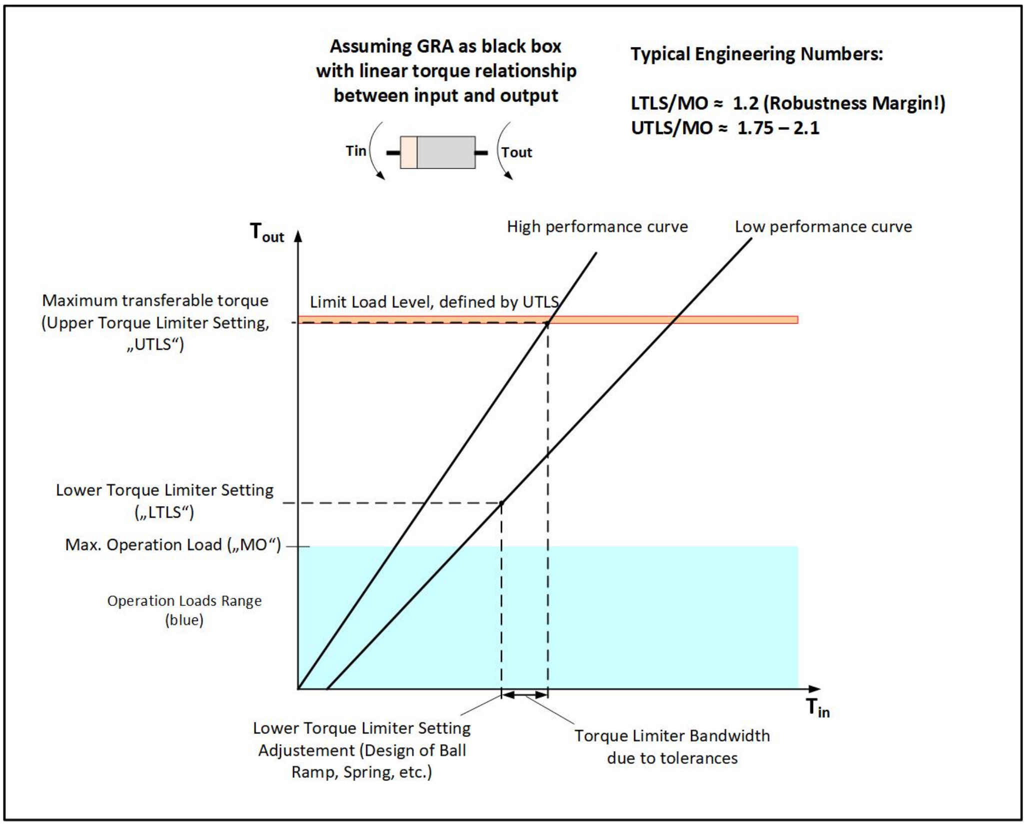


Figure 1-3

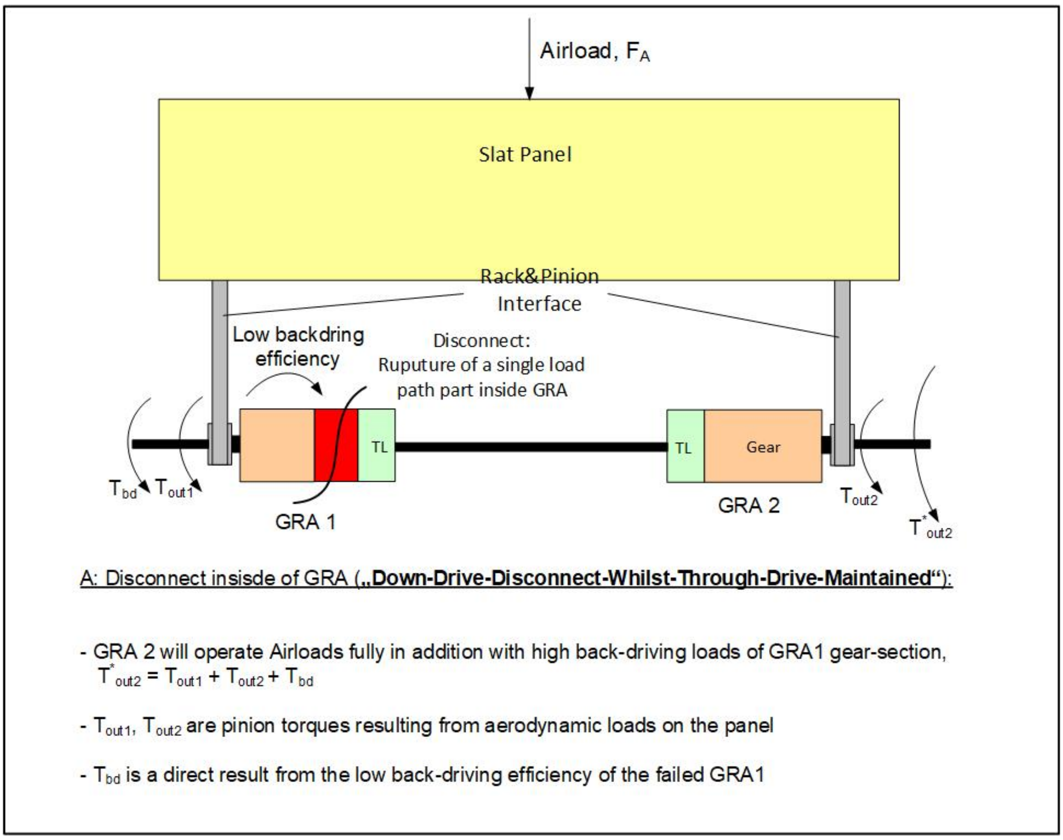


Figure 2-1

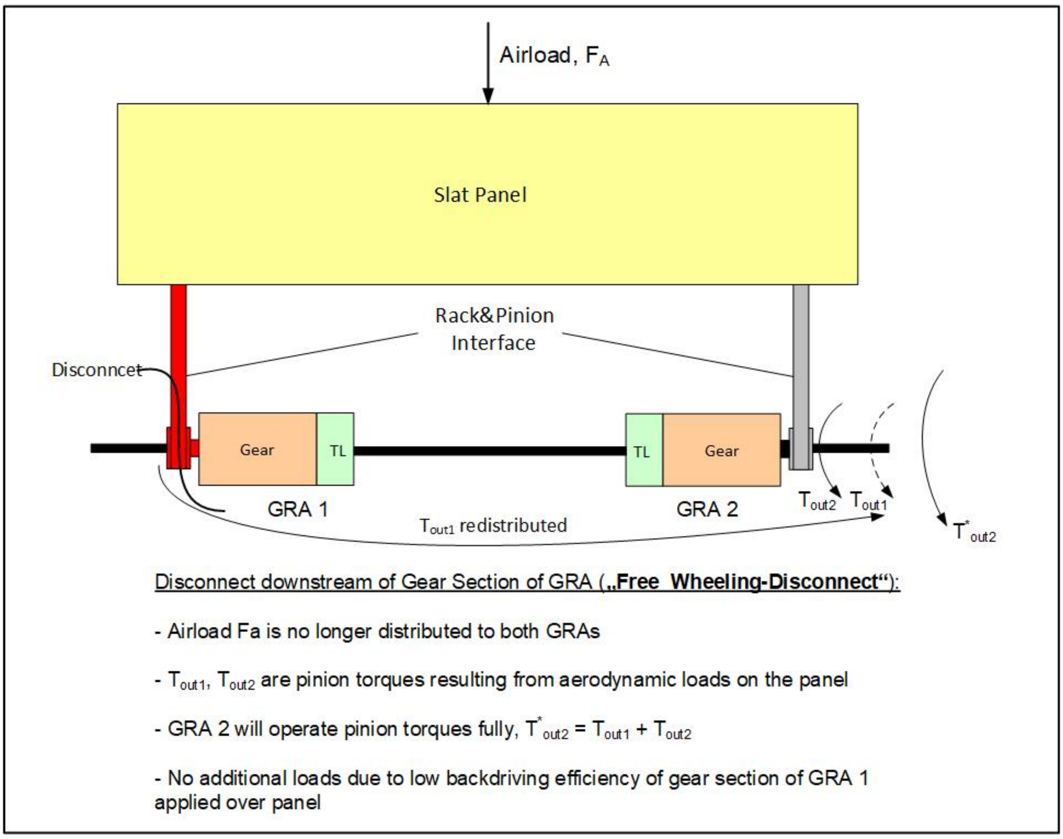


Figure 2-2

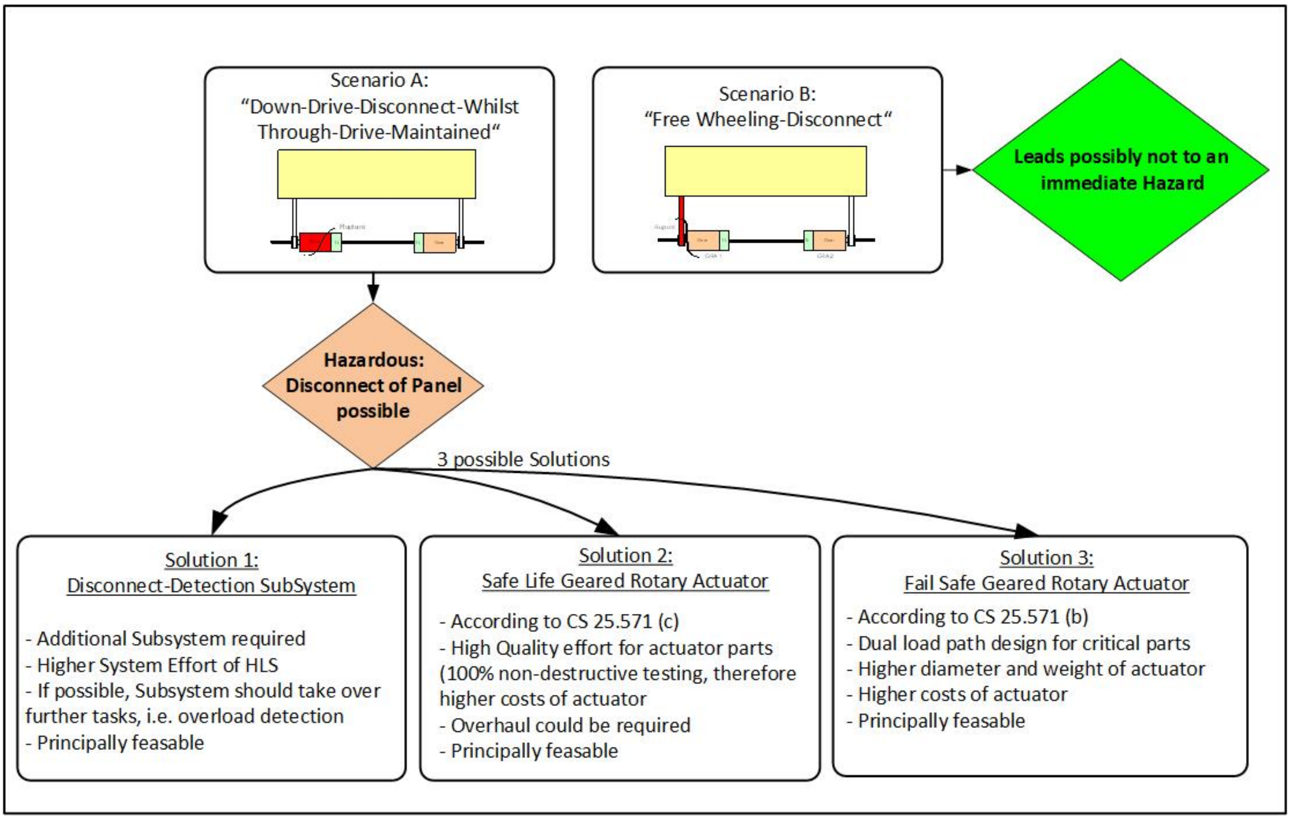


Figure 2-3

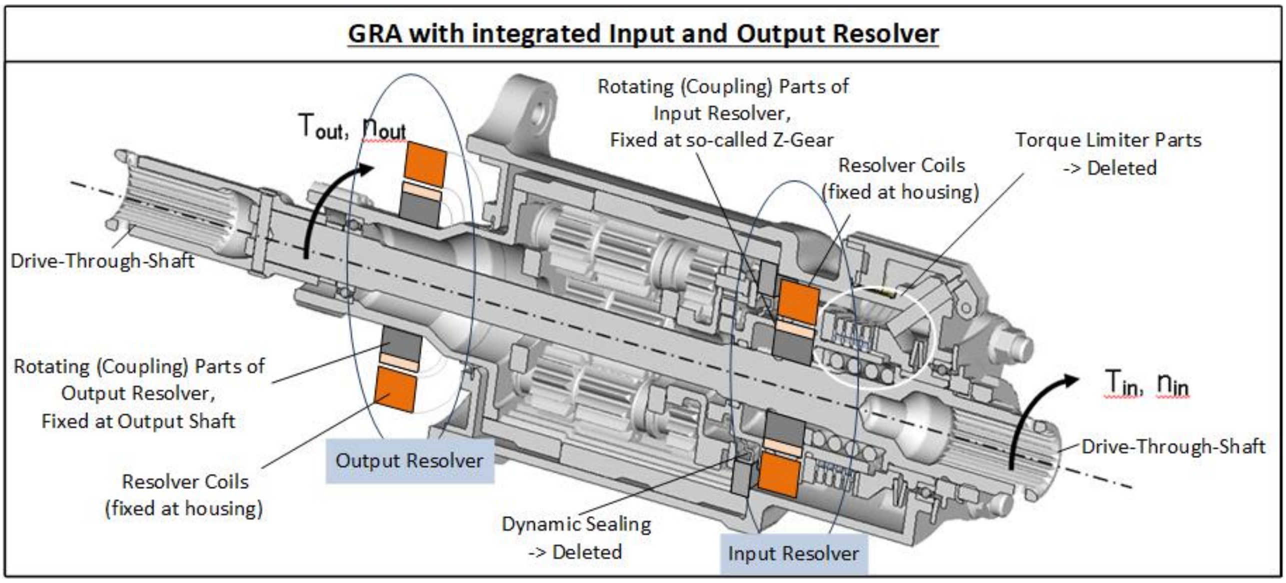


Figure 3-1

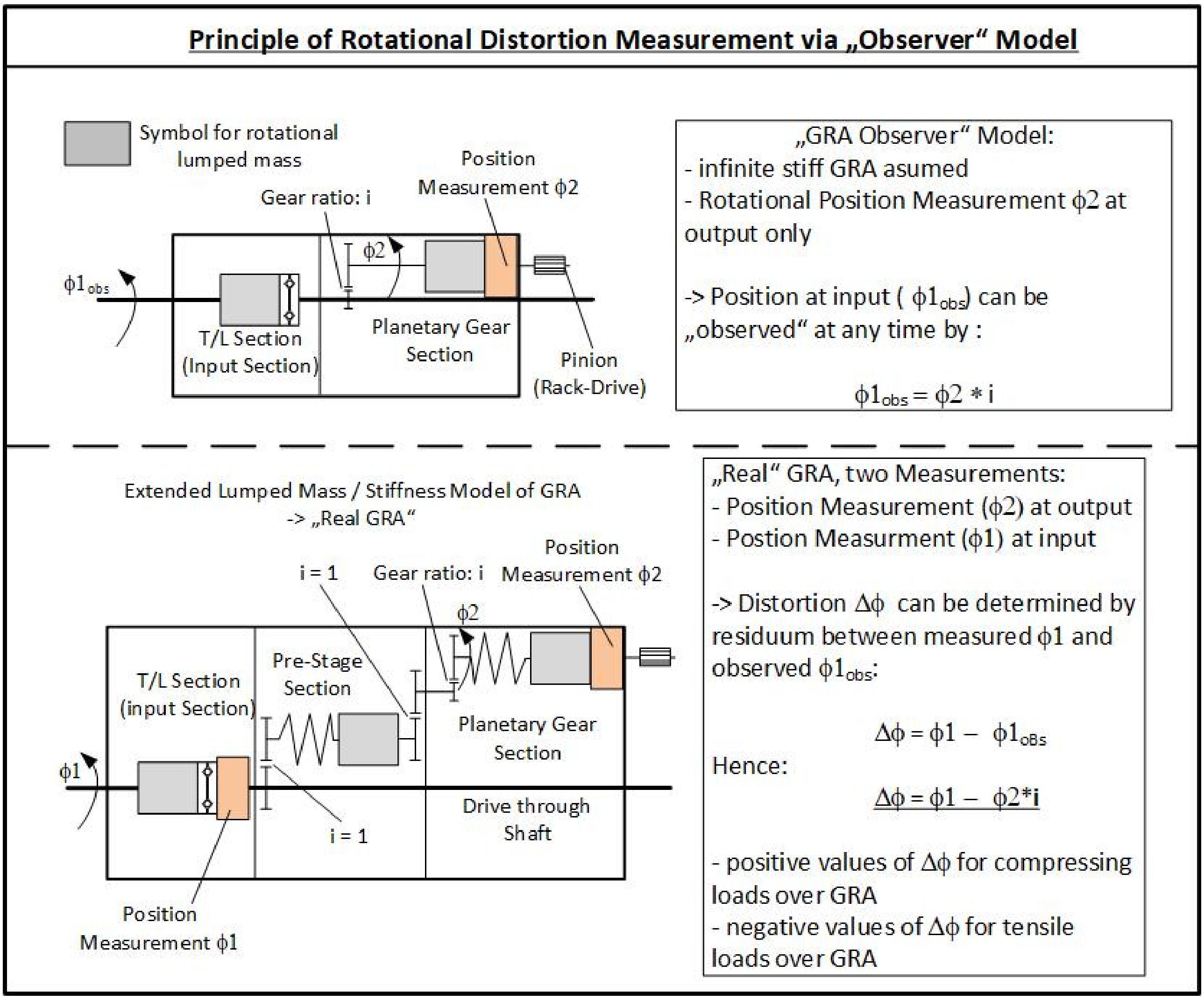
Principle of Rotational Distortion Measurement via „Observer" Model
Symbol for rotational lumped mass
Gear ratio: i
Position Measurement ϕ2
ϕ2
ϕ1obs
T/L Section (Input Section)
Planetary Gear Section
Pinion (Rack-Drive)
„GRA Observer" Model:
- infinite stiff GRA asumed
- Rotational Position Measurement ϕ2 at output only
-> Position at input ( ϕ1obs) can be „observed" at any time by :
ϕ1obs = ϕ2 * i
Extended Lumped Mass / Stiffness Model of GRA
-> „Real GRA"
i = 1
Gear ratio: i
Position Measurement ϕ2
ϕ2
T/L Section (input Section)
Pre-Stage Section
Planetary Gear Section
ϕ1
i = 1
Drive through Shaft
Position Measurement ϕ1
„Real" GRA, two Measurements:
- Position Measurement (ϕ2) at output
- Postion Measurment (ϕ1) at input
-> Distortion Δϕ can be determined by residuum between measured ϕ1 and observed ϕ1obs:
Δϕ = ϕ1 – ϕ1oBs
Hence:
Δϕ = ϕ1 – ϕ2*i
- positive values of Δϕ for compressing loads over GRA
- negative values of Δϕ for tensile loads over GRA

Figure 3-2

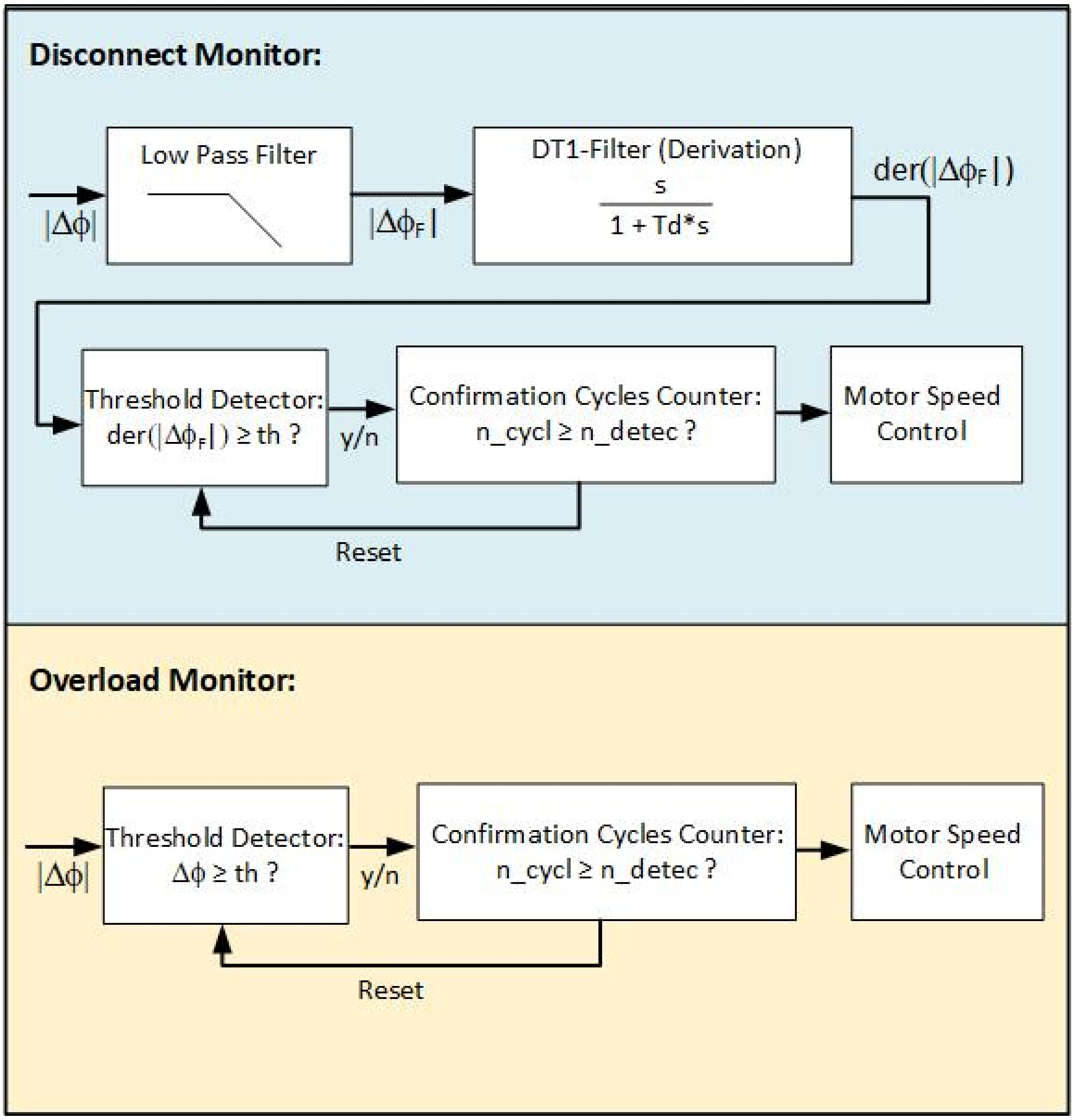
Disconnect Monitor:
|Δϕ|
Low Pass Filter
|ΔϕF|
DT1-Filter (Derivation)
s
1 + Td*s
der(|ΔϕF|)
Threshold Detector:
der(|ΔϕF|) ≥ th ?
y/n
Confirmation Cycles Counter:
n_cycl ≥ n_detec ?
Motor Speed
Control
Reset
Overload Monitor:
|Δϕ|
Threshold Detector:
Δϕ ≥ th ?
y/n
Confirmation Cycles Counter:
n_cycl ≥ n_detec ?
Motor Speed
Control
Reset

Figure 4-1

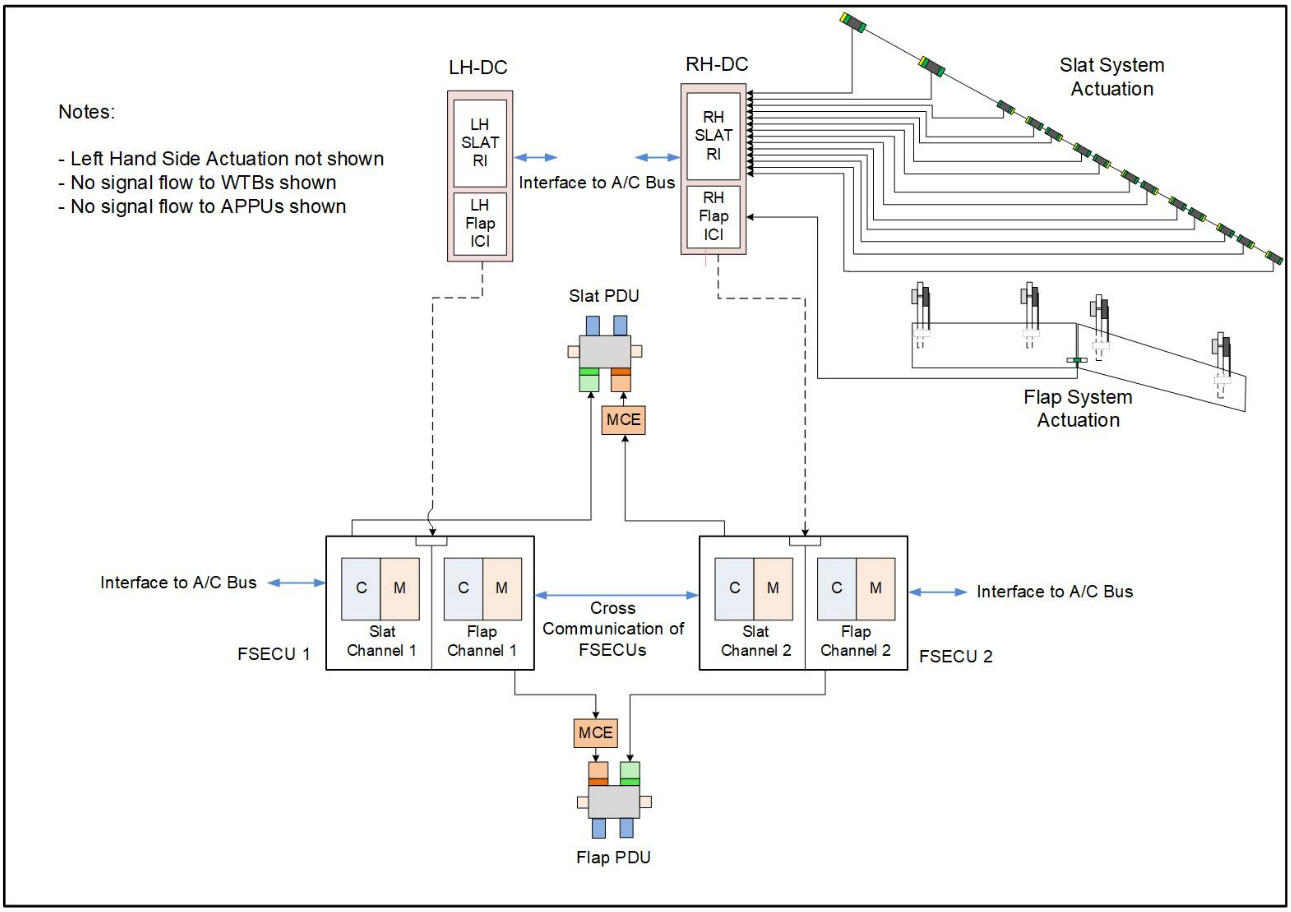
Notes:
- Left Hand Side Actuation not shown
- No signal flow to WTBs shown
- No signal flow to APPUs shown
LH-DC
LH SLAT RI
LH Flap ICI
RH-DC
RH SLAT RI
RH Flap ICI
Interface to A/C Bus
Slat System Actuation
Flap System Actuation
Slat PDU
MCE
Interface to A/C Bus
C
M
Slat Channel 1
Flap Channel 1
FSECU 1
Cross Communication of FSECUs
Slat Channel 2
Flap Channel 2
FSECU 2
Interface to A/C Bus
MCE
Flap PDU

Figure 5-1

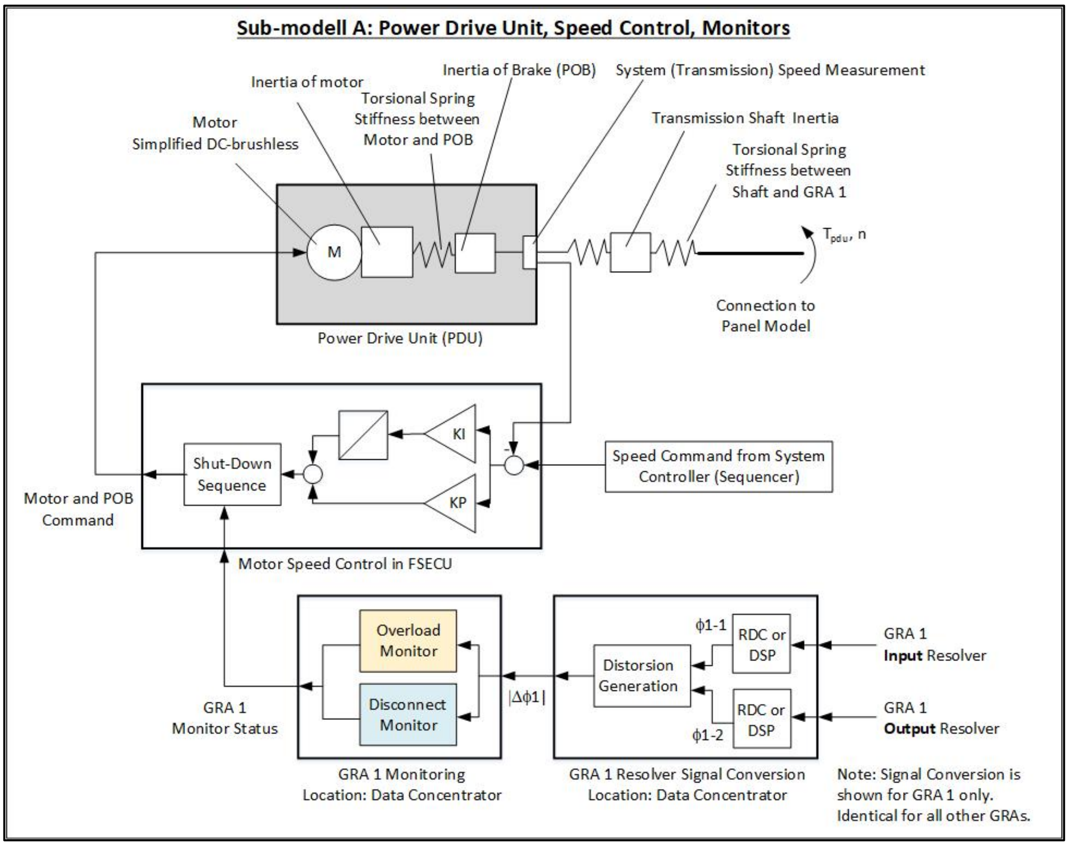


Figure 6-1

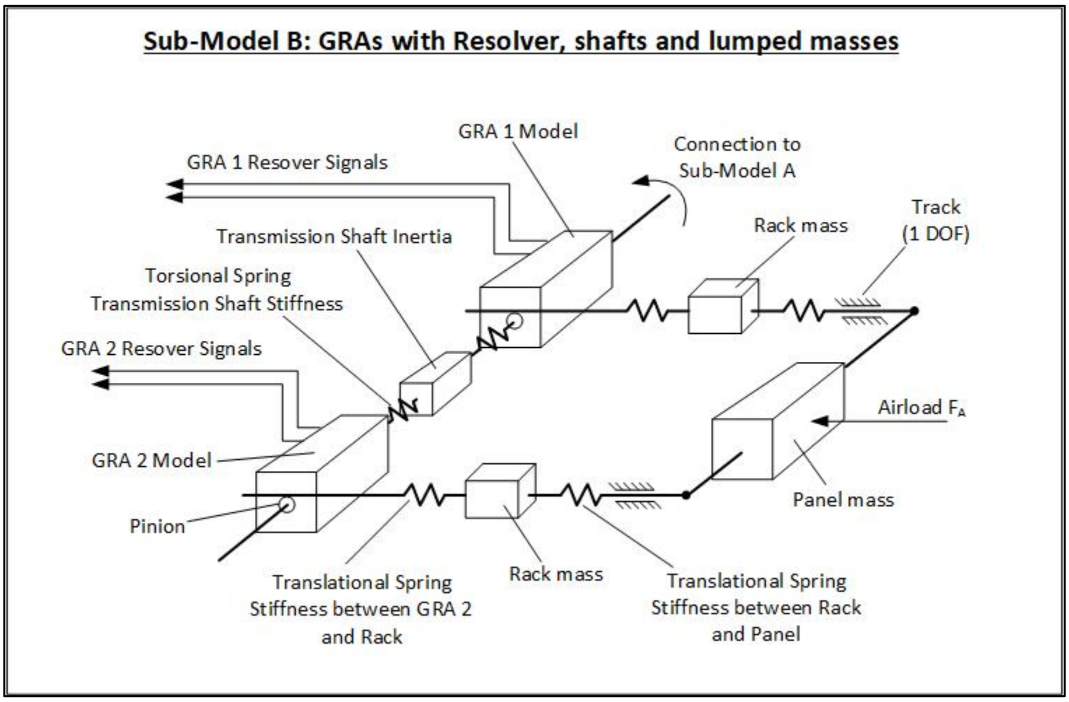


Figure 6-2

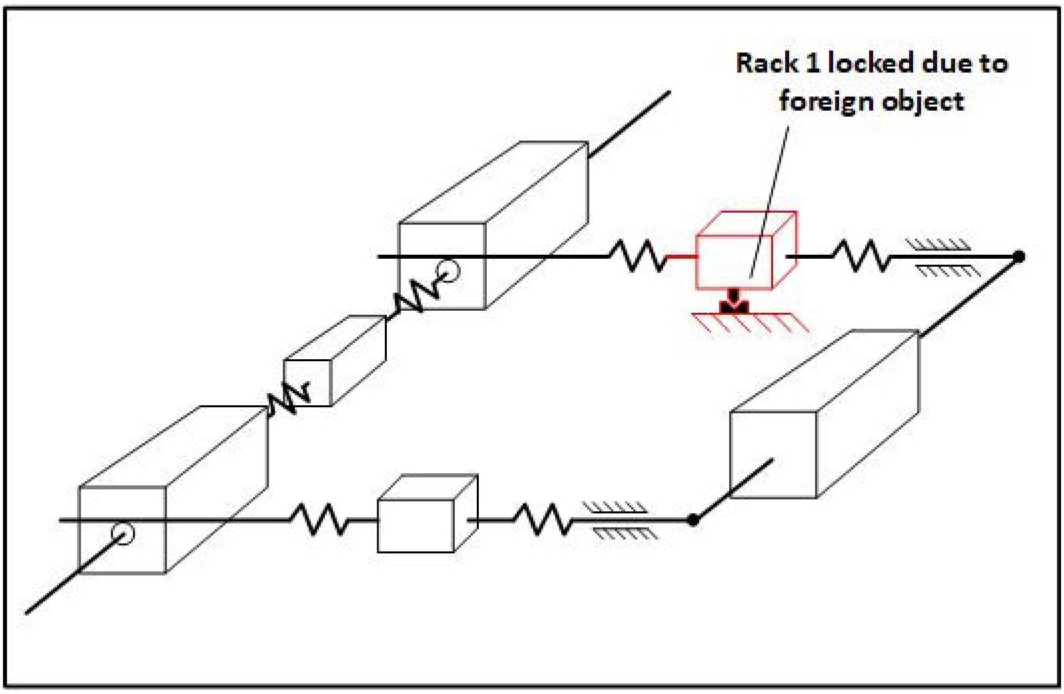


Figure 6-3

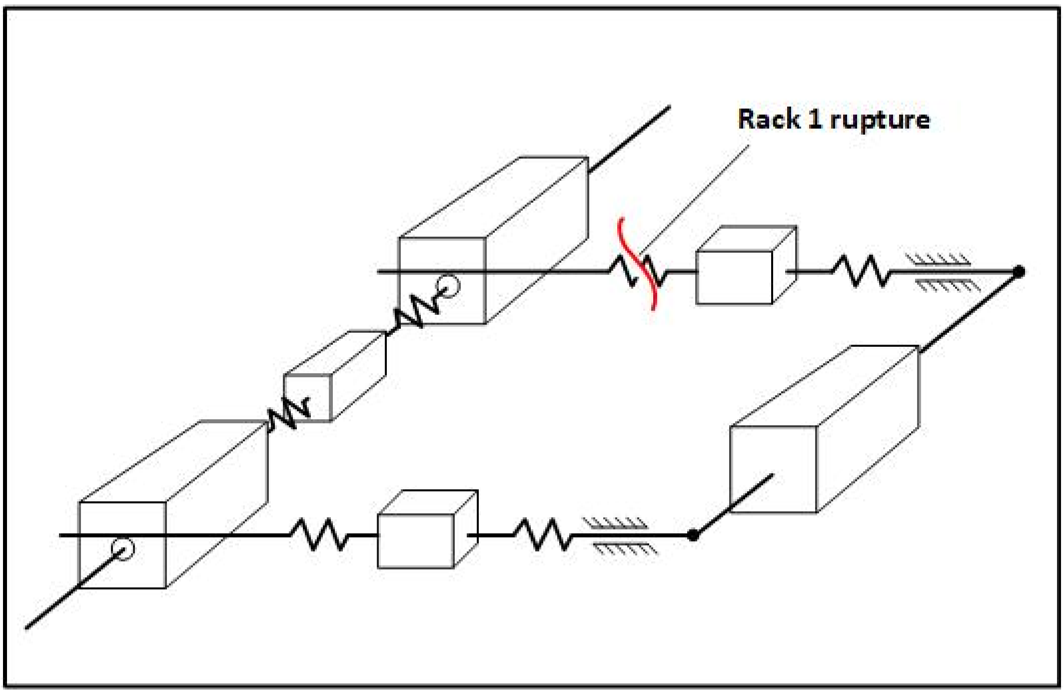


Figure 6-4

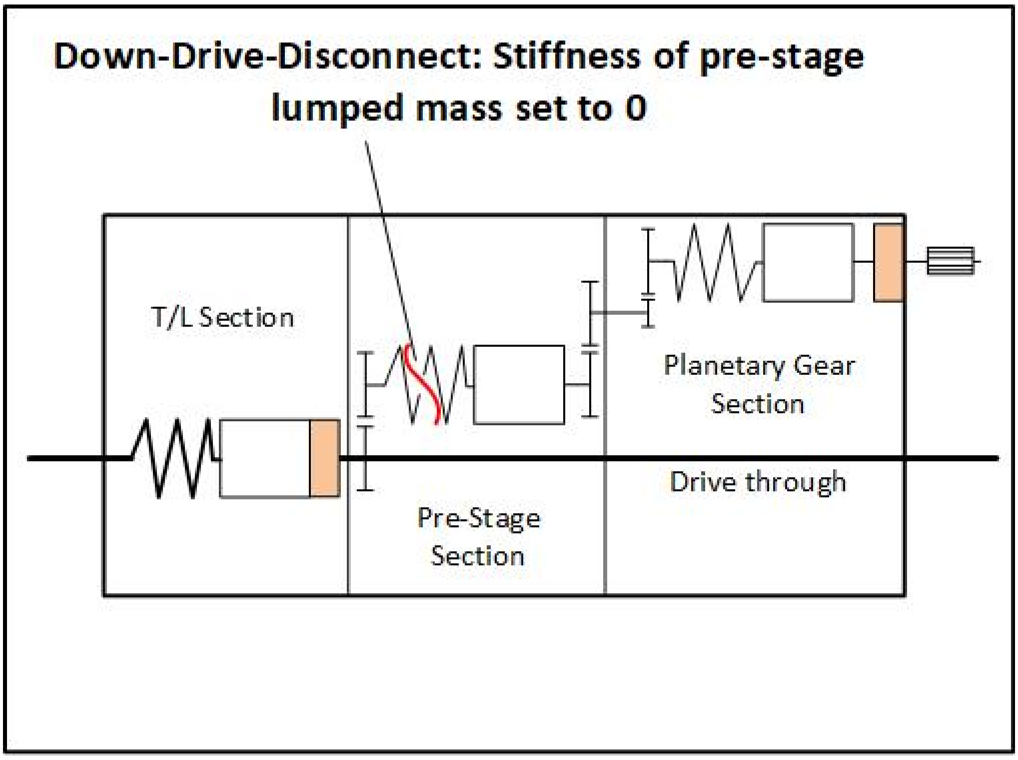
Down-Drive-Disconnect: Stiffness of pre-stage lumped mass set to 0
T/L Section
Planetary Gear Section
Drive through
Pre-Stage Section

Figure 6-5