Active Control Technology for Tiltrotor Structural Load Alleviation

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Abstract

Several components of the tiltrotor propulsion system are being exposed to unacceptable levels of loading. The goal of the present paper is to present structural load alleviation (SLA) solutions reducing (improving) the critical loads of the interconnect drive shaft and the elastomeric flapping bearing. These solutions are using the FLIGHTLAB ERICA simulation model developed in the framework of the ACT-TILT project. The ACT-TILT Critical Technology Project (CTP) is part of the 5th Framework Research Programme of the European Union and is aiming to design a Flight Control System (FCS) for an advanced European Tilt-Rotor configuration. This study was performed as a Master of Science project in collaboration between Delft University of Technology and the Dutch National Aerospace Laboratory NLR. Off-line simulations performed in this paper indicated that the interconnect drive shaft is subject to a high twisting moment in airplane mode whenever a roll rate or yaw rate is present. Therefore, a system called Differential Torque Alleviation System (DTAS) was designed in the paper to reduce the critical loads on the interconnect drive shaft. This system uses roll rate, yaw rate and airspeed as feedback to give differential collective pitch inputs. Piloted simulation tests performed in the fixed-based simulator of The Dutch National Aerospace Laboratory (NLR) and in the motion-based simulator of the University of Liverpool proved that DTAS reduced the structural loads by about 90% while improving handling qualities by approximately 2 Cooper-Harper rating points. Furthermore, the paper proved that the elastomeric flapping bearing is subject to high fatigue loading in conversion mode flight due to high steady state flapping angles. Thus, the Flapping Reduction System (FRS) was designed for this study effectively reducing the steady state flapping angles to an acceptable level by giving elevator commands. Piloted simulation tests proved that this system can be used for alleviating the structural loads while not affecting at all handling qualities. In conclusion, the exercise of the paper proved that active control technology can be successfully used to reduce structural loads on tiltrotor aircraft without degrading handling qualities.

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List of symbols and abbreviations

a_0	coning angle [rad]
a_1	longitudinal disc tilt angle w.r.t. the plane of no-feathering (also called longitudinal flapping) [rad]
b_1	lateral disc-tilt angle w.r.t. the plane of no-feathering; (also called lateral flapping) [rad]
$a_2....a_n$	cosine components in the flapping motion as represented by an infinite Fourier series [-] (see equation 1);
$b_2...b_n$	sine components in the flapping motion as represented by an infinite Fourier series [-] (see equation 1);
H_p	Pressure height [ft]
K_{dcp}	relationship between differential collective pitch, airspeed and differential torque;
K_p	relationship between roll rate, airspeed and differential torque
K_r	relationship between yaw rate, airspeed and differential torque
p	roll rate [rad/s]
r	yaw rate [rad/s]
V	airspeed [kts]
β	flapping angle [rad]
β_{max}	maximal flapping angle [rad]
δ_e	elevator deflection angle [rad]

$\delta_{e,extra}$	extra elevator deflection angle commanded by flapping reduction system [rad]
$\dot{\delta}_e$	elevator deflection rate [rad/s]
$\dot{\delta}_{e,extra}$	extra elevator deflection rate commanded by flapping reduction system [rad/s]
θ_0	collective pitch angle [rad]
$\theta_{0,l}$	collective pitch angle of the left prop-rotor [rad]
$\theta_{0,r}$	collective pitch angle of the right prop-rotor [rad]
Ω	prop-rotor rotational speed [rad/s]
Ω_{cr}	critical shaft rotational speed [rad/s]
ψ	azimuth angle [rad]

AC	Alternating Current
DC	Direct Current
CTP	Critical Technology Project
ACT-TILT	Active Control Technologies for TILT-rotor
DCP	Differential Collective Pitch
DTAS	Differential Torque Alleviation System
ERICA	Enhanced Rotorcraft Innovative Concept Achievement
FRS	Flapping Reduction System
HPS	Helicopter Pilot Station of the NLR
IAS	Indicated Airspeed
ISA	International Standard Atmosphere
MTE	Mission Task Element
MTOW	Maximum Takeoff Weight
MWGB	Mid Wing Gearbox
PRGB	Prop-Rotor Gearbox
SLA	Structural Load Alleviation
TAGB	Tilt-Axis Gearbox

Introduction

Designing the propulsion system for a tiltrotor aircraft involves the accomplishment of two contradictory constraints giving, on the one side, the ability of the tiltrotor to fly fast and efficiently in forward flight like a turboprop airplane and, on the other side, the possibility to take off, hover, and land vertically like a conventional helicopter. Several structural components must thus be implemented in a propulsion system of the tiltrotor, systems that are not used in either conventional helicopter or turboprop designs. King et. al. [ref. 1] investigated what are the most highly loaded (critical) components of a tiltrotor propulsion system when flying different flight test manoeuvres with the Bell-Boeing V-22 'Osprey'. Their results showed that mainly three components are critical, i.e. 1) the interconnect drive shaft, 2) the elastomeric flapping bearing and 3) the rotor yoke. All these components are being exposed to unacceptable levels of loading. Consequently, on these components, Structural Load Alleviation (SLA) techniques making use of active control of structural loads should be applied in order to prevent load exceedances. Miller and Ham [ref. 2] and later Manimala and Padfield [ref. 3] explored SLA systems applied in order to reduce the loads on the rotor yoke. The goal of the present paper is to develop SLA solutions particularly for alleviating the critical loads on the first two mentioned critical components of the tiltrotor propulsion system, i.e. interconnect drive shaft and elastomeric flapping bearing.

The simulation model used in the current work is the FLIGHTLAB ERICA simulation model. This model [ref. 7] was developed in the 5th Framework, European Union funded, 'Critical Technology Project' (CTP) ACT-TILT (Active Control Technologies for TILT rotor), in which NLR is one of the partners. ACT-TILT aims to develop the Flight Control System (FCS) for an advanced European Tilt-Rotor configuration (ERICA - Enhanced Rotorcraft Innovative Concept Achievement).

The paper is structured as follows:

- The first section describes the components of the propulsion system of a conventional tiltrotor aircraft;
- The second section illustrates the characteristics of the simulation model used for tiltrotor propulsion system analysis;
- The third section determines the critical loads in interconnect shaft and the elastomeric flapping bearing;
- The fourth section describes the design and evaluation of SLA systems for the interconnect drive shaft and the elastomeric flapping bearing;

- Finally, general conclusions and recommendations to this work are discussed.

Tiltrotor propulsion systems

The propulsion system of a tiltrotor consists of the engines, the prop-rotors, and all the shafts, gearboxes and other parts interconnecting the engines with the prop-rotors. Together, these parts and shafts are called the drive train system. In a normal configuration, tiltrotor aircraft have two engines and two counter-rotating prop-rotors, all located at the wing tips. Figure 1 presents a generic picture of the tiltrotor propulsion system. The left and right prop-rotor are connected to each other with an interconnect shaft through the wing to make sure that both prop-rotors always maintain the same rotational speed. This is very important for two reasons. The first reason is safety. One can imagine that a very dangerous situation occurs whenever there is an engine failure during helicopter mode flight. The power of the operating engine can be transferred to both prop-rotors due to the presence of the interconnect shaft. Whenever there is a one-engine inoperative situation in helicopter mode, the aircraft can quickly tilt the nacelles forward and fly in conversion mode or airplane mode and make a safe landing in conversion mode. Two one-way clutches (free wheels) are provided to disengage the engine in case of engine failure. The second reason is to keep the rotational speed of both prop-rotors constant during aggressive manoeuvring. The propulsion systems of the Bell-Boeing V-22 'Osprey' and the Bell-Agusta BA-609 are very similar and typical for tiltrotor propulsion systems. The clutches are not displayed in Figure 1 for the sake of clarity. Looking at Figure 1, one can see that the power of the engines is transmitted to the prop-rotor gearbox (PRGB) through the engine shafts. These engine shafts rotate at a very high speed. This high rotational speed of the engine is reduced with the prop-rotor gearbox (PRGB). The engine power is then transferred from the prop-rotor gearboxes to the prop-rotors. The tilt-axis gearbox is a connecting part between the nacelle and the interconnect shaft within the wing. The interconnect drive shaft consists of two parts connected to each other with the mid-wing gearbox (MWGB). The gearboxes are used not only to reduce or increase rotational speeds of shafts, but also to mount accessories on parts such as DC-generators, AC-generators, heat exchangers, lubrication pumps and hydraulic pumps. In the figure it looks like the interconnect drive shaft consists of two long shafts. However, this is not completely correct. The interconnect drive shaft is made of several relatively short segments in reality. The reason for a number of relatively short segments is to ensure the dynamic stability of the interconnect drive shaft.

There is a critical rotational speed of the shaft at which bending will become unstable. This critical speed Ω_{cr} is the first bending mode natural frequency. So the dynamic stability of the interconnect shaft is ensured when the operational speed is kept below Ω_{cr}. It is desirable to have a high operational speed (this will be explained later on) and thus the critical speed should be high too. A short shaft has a higher first bending mode natural frequency and this is why the interconnect shaft is divided into segments. Designs for supercritical shaft systems are already available [ref. 6]. Supercritical shaft systems are systems that have an operational speed above the critical speed. This means that when such a drive system is started it should go through the critical operating speed. It is beyond the scope of this paper to explain exactly how these systems work. But it is important to realise that supercritical shaft systems can operate at very high rotational speeds and it is not necessary to divide long shafts into short segments. These systems therefore have a lower weight, a higher reliability, and they are cheaper. Tiltrotor technology is relatively new and the introduction of tiltrotor aircraft on the market is, therefore, not without risk. Thus, designers like to use conventional proven technology as much as possible within the tiltrotor design to reduce risk. Supercritical shaft systems therefore have not yet been implemented. In order to get some "feeling" for the technical characteristics of a tiltrotor propulsion system, Table 1 summarises some data of such a system as available on Bell-Boeing V-22 'Osprey' and Bell-Agusta 609.

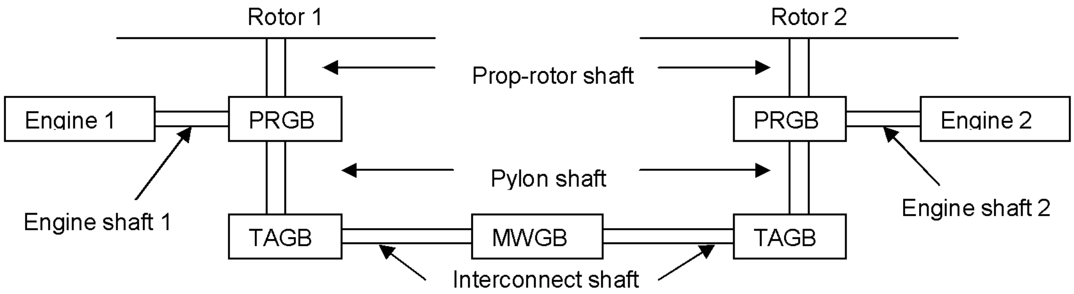

Figure 1: Propulsion system of the V-22 and BA-609 [refs. 4, 5]

Propulsion system parameters	Bell-Boeing V-22 'Osprey'	Bell-Agusta 609
Engine shaft speed [rpm]	15000	30032
Pylon shaft speed [rpm]	11905	8302
Interconnect speed [rpm]	6547	6536
Prop-rotor speed [rpm]	397	569
Mast transient power [hp]	5040	1725
Mast maximum continuous power [hp]	4200	1738
Engine input power (OEI) [hp]	5700	2300
Rotational speed reduction in airplane mode [%]	16	16

Table 1: Typical tiltrotor propulsion system characteristics in airplane mode flight [refs. 4,5]

One can see that there are large differences in the rotational speeds of the shafts. The engine shaft speed purely depends on the type of engine used. The prop-rotor is designed for a certain constant rotational speed and the mast rotates at this speed. The interconnect drive shaft speed can be set by the designer at any speed below the critical speed. The interconnect drive shaft is subject to a twisting moment due to torque differences between the left and right prop-rotor during asymmetric manoeuvres and during OEI flight. The torsional deformations of the interconnect drive shaft should not be too high for two reasons:

- Fatigue loading on the shaft
- The left and right prop-rotor speed should be the same during asymmetric manoeuvres

Assuming that there is no power loss in the gearboxes, then the transmitted power through a drive shaft is simply the multiplication of rotational speed and torque. This means that the twisting moment on the interconnect shaft is reduced when its rotational speed is higher than that of the prop-rotor mast. So, a high rotational speed results in a low torque and is, therefore, wanted. The interconnect drive shaft speed should not be too high to ensure dynamic stability of the drive system. Apparently, there is an optimal interconnect shaft speed of about 6000 rpm in general for a conventional tiltrotor configuration. The Bell-Boeing V-22 'Osprey' has engines with more power because of its larger size and the fact that it is a military aircraft. The shaft speeds are reduced in airplane mode flight to improve efficiency. The prop-rotor rotational speed is reduced by about 20% for normal tiltrotor configurations.

FLIGHTLAB Tiltrotor Simulation Model

The simulation model used in the present investigation is the FLIGHTLAB ERICA simulation model (figure 2). As mentioned above, this model [ref. 7] has been developed in the 5th Framework, European Union funded, 'critical technology' project ACT-TILT and aims to develop the Flight Control System (FCS) for the advanced European Tilt-Rotor configuration ERICA

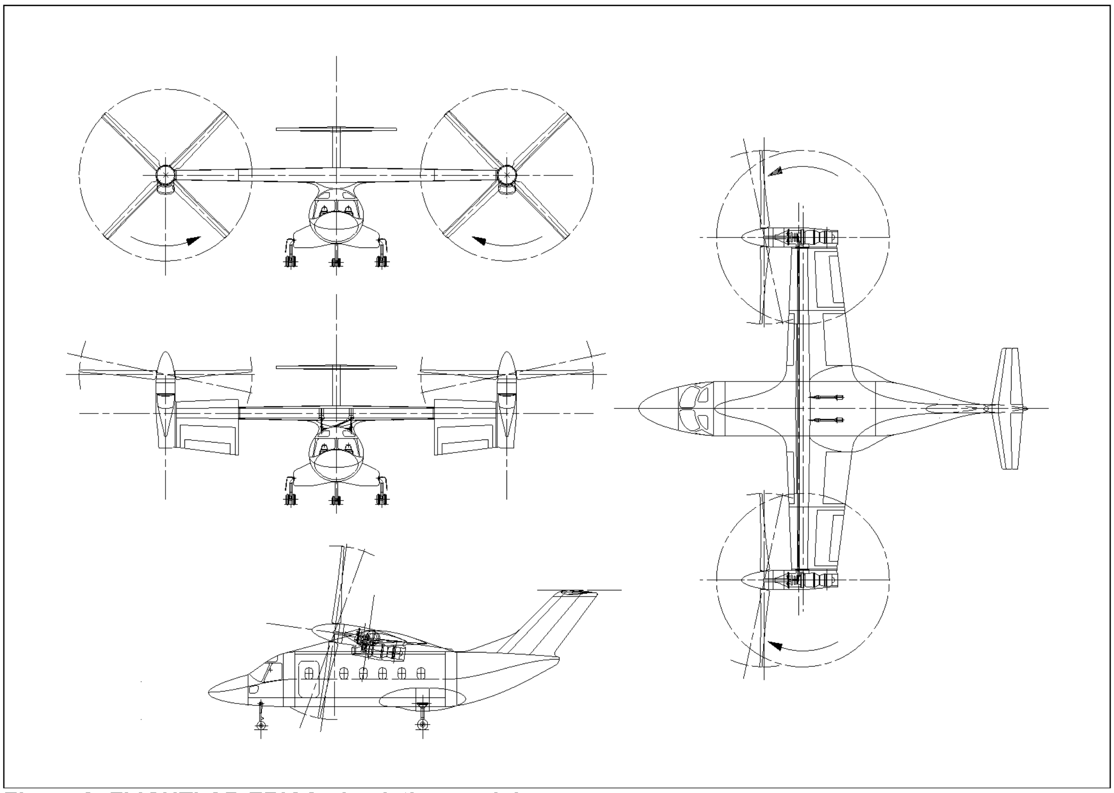

Figure 2: FLIGHTLAB ERICA simulation model

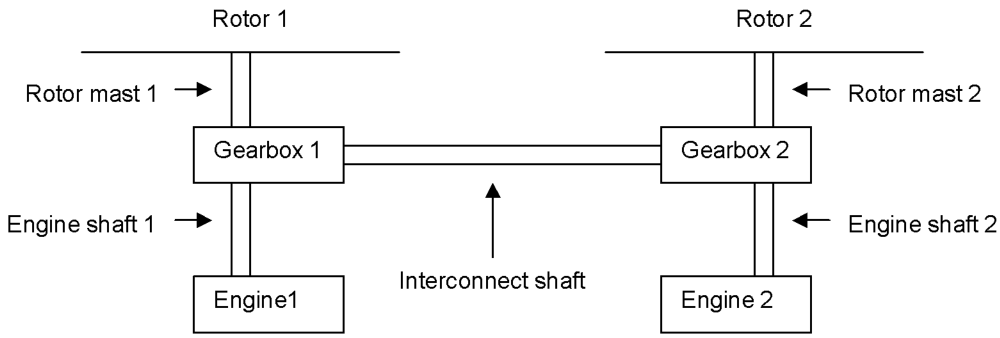

Figure 3: FLIGHTLAB ERICA simulation model propulsion system

FLIGHTLAB is an advanced simulation environment for rotorcraft analysis with a modular structure, enabling to build rotorcraft models of varying levels of complexity [ref. 8]. The FLIGHTLAB ERICA model is a conventional civil tiltrotor model. The simulation model has the following main characteristics:

- 2 counter rotating 4-bladed prop-rotors
- Stiff in-plane prop-rotor with a homo kinetic gimballed hub
- Peters/He 3-state rotor inflow model

A good model of the propulsion system has to be available in order to simulate the structural loads on the interconnect drive shaft and the elastomeric flapping bearing correctly. This means that accurate calculations of the engine dynamics, the prop-rotor dynamics and the torsional dynamics of the drive train are necessary. A simplified scheme of the propulsion system as used by the FLIGHTLAB ERICA model is displayed in Figure 3.
The power from the engines is distributed through the engine shafts to the gearboxes.

The rotational speed is lowered there to the prop-rotor rotational speed. The prop-rotors are connected to the gearboxes with a prop-rotor mast. One can also see the presence of the interconnect shaft, which couples both prop-rotor speeds. In FLIGHTLAB ERICA model the shafts are modelled as flexible shafts. They have a stiffness and damping and can twist linearly. So the FLIGHTLAB ERICA model drive train is a flexible drive train. The engines, which are type 2500 hp class, are modelled as two separate thermodynamic engine models [ref. 9]. The advantage of two separate engine models combined with a flexible drive train is that engine failures can be simulated very realistically. The FLIGHTLAB ERICA model is used in offline simulations to determine the critical loads on the interconnect drive shaft and elastomeric flapping bearing.

<u>Critical loads on the interconnect drive shaft</u>

King. et. al. [ref. 1] using actual flight test data investigated the critical manoeuvres with respect to structural loads on the interconnect drive shaft for the Bell-Boeing V-22 'Osprey'. It was concluded that the interconnect drive shaft is highly loaded for high roll rate manoeuvres in airplane mode. This can be explained physically with Figure 4.

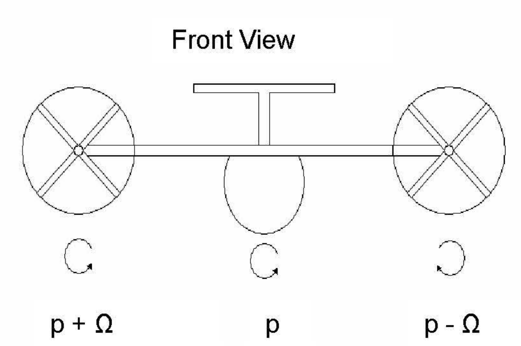

Figure 4: Physical cause of differential torque due to a roll rate in airplane mode

A roll rate (*p*) essentially means that the two prop-rotors have a different rotor speed with respect to the airflow. A difference between the prop-rotor speeds results in a torque difference. The interconnect drive shaft is loaded whenever there is a torque difference between the left and right prop-rotor. This torque difference will be called from now on differential torque.

The goal of the present paper is to investigate the effect of asymmetrical manoeuvres in airplane mode on the interconnect drive shaft loading. For this, with the FLIGHTLAB ERICA model in airplane mode, a series of off-line simulations will be performed in order to investigate the effect of a roll rate (p) or a yaw rate (r) on differential torque. The results of these simulations are summarised in Figure 5.

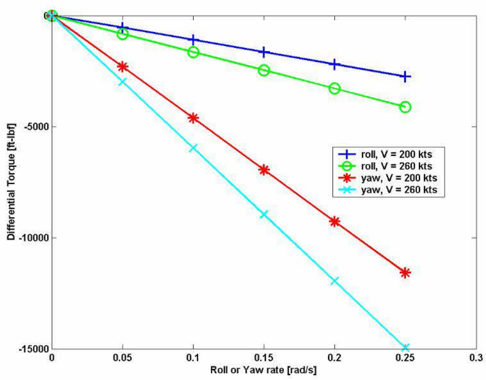

Figure 5: The correlation between a roll or yaw rate and differential torque in airplane mode flight

Looking at Figure 5 one may see that, concerning the interconnect drive shaft, searching for the critical flight scenarios when flying off-line the FLIGHTLAB ERICA model, the highest loads are achieved when performing high roll rate and yaw rate manoeuvres in airplane mode. The flight speed also has a large effect on the loads. A higher flight speed results in a linearly higher loading during asymmetrical manoeuvres. As mentioned before, the conclusion that high critical loads can be developed on the interconnect drive shaft during high roll rate manoeuvres has already been revealed in the literature [ref. 1] when flying the Bell-Boeing V-22 'Osprey'. However it has never appeared that this would be the case when flying high yaw rate manoeuvres! The results show that a yaw rate introduces a structural load on the interconnect drive shaft twice as large as that of a roll rate. One must not forget that, in actual flight, higher roll rates are achieved than yaw rates. Nevertheless the effect of a yaw rate on differential torque in actual flight will be very significant. Physically this effect can be explained when looking at Figure 6.

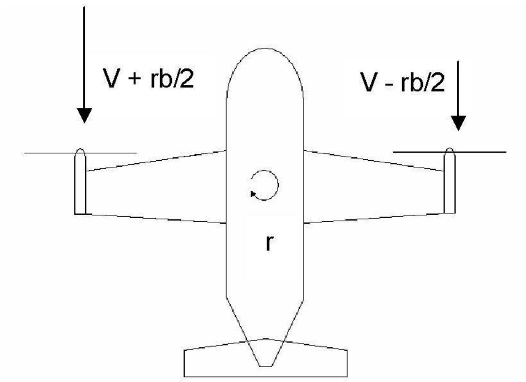

Figure 6: Physical cause of differential torque due to a roll rate in airplane mode

The introduction of a positive yaw rate in airplane mode causes a larger airflow through the left prop-rotor and a smaller airflow through the right prop-rotor. This results in an increase of the left prop-rotor torque and a decrease of the right prop-rotor torque and thus in a differential torque. The results presented in Figure 5 will be used later on in this paper for SLA system design using active control technology.

<u>Critical loads on the elastomeric flapping bearing</u>

Flight tests and research studies performed with the Bell-Boeing V-22 'Osprey' [ref. 1] have indicated that steady state prop-rotor flapping angles up to 6° are achieved during trimmed flight. The highest flapping angles are achieved with a forward centre of gravity position and a nacelle angle of 60°. However, ref. 1 does not state anything about nacelle angles smaller than 60° so, it is not quite sure what the flapping angles are at other nacelle angles. Fatigue tests on the Bell-Boeing V-22 'Osprey' have indicated that flapping angles greater than 4° degrade the elastomeric flapping bearing life. A system that can reduce the steady state flapping angles in forward flight has therefore been designed for the Bell-Boeing V-22 'Osprey.

The simulation model FLIGHTLAB ERICA model used in this paper is designed such that flapping angles may never exceed 10° for clearance. There is no information available on fatigue of the elastomeric flapping bearings of the FLIGHTLAB ERICA model prop-rotor at this moment. However, if the flapping angles are high, then one can assume that a steady state flapping angle reduction system for the FLIGHTLAB ERICA model would be very useful too. A number of trim sweeps for various centre of gravity positions, nacelle angles and flight speeds are performed to investigate the steady state flapping angles for the FLIGHTLAB ERICA model. The trim sweeps (figures 7 – 9) are done for the following flight conditions.

- Maximum take-off weight (MTOW)
- Height 90 ft (ISA)
- Level flight

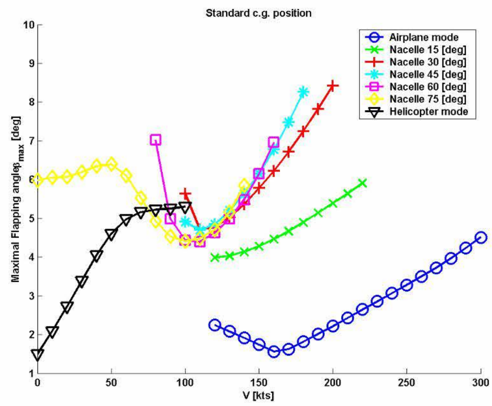

Figure 7: Trim sweep for the neutral centre of gravity position

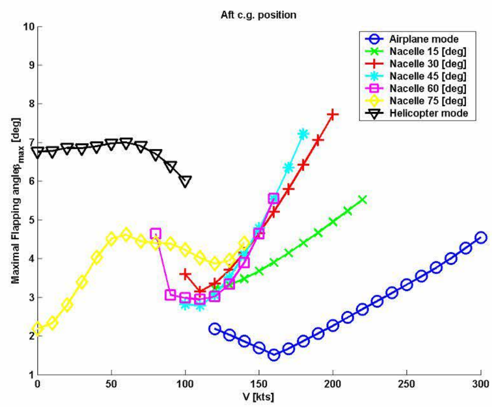

Figure 8: Trim sweep for the maximal aft centre of gravity position

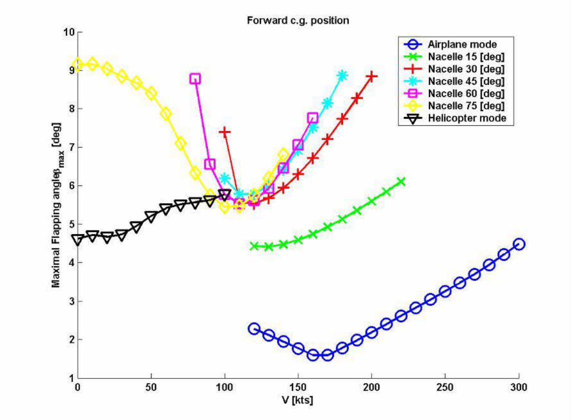

Figure 9: Trim sweep for the most forward centre of gravity position

The trim sweeps are performed from the low speed boundary of the conversion corridor to the high-speed boundary. From these figures a number of conclusions can be drawn concerning the trim sweeps. Generally, the greatest flapping angles are achieved during high-speed conversion mode flight with nacelle angles varying from 30° to 60°. The flapping angles are greatest when the centre of gravity is in its most forward position (see Figure 9). Flapping angles of about 9°, which are very close to the design clearance limit, are in this case already reached. Concluding, it can be deduced that a steady state flapping angle reduction system should be additionally designed for the FLIGHTLAB ERICA model.

Structural Load Alleviation system design for the interconnect drive shaft

The strong correlation between roll rate, yaw rate, airspeed and differential torque is used as a starting point for SLA system design. The SLA system for the interconnect drive shaft will be called the Differential Torque Alleviation System (DTAS). DTAS has a very simple working principle. First, the differential torque that will develop due to asymmetrical manoeuvring has to be predicted. The prediction can be done because the correlation between a roll or yaw rate and differential torque in airplane mode flight is known (see figure 5). A differential collective pitch will then be generated by DTAS. The differential torque generated by the differential collective pitch should be exactly of the same magnitude and opposite sign of the predicted differential torque. As a result, DTAS should reduce the structural load on the interconnect drive shaft by almost 100% if the load prediction by the system is correct. The system is illustrated in Figure 10. The Block K_p is a look-up table describing the (almost linear) relationship between roll rate, airspeed and differential torque. It is in fact a more detailed version of above-plotted Figure 5. So the output of this block is a predicted value of differential torque due to roll rate. This predicted value is summed with the predicted differential torque due to a yaw rate (block K_r). The predicted differential torque is then multiplied with minus 1 and used as input for the block K_{dcp}. This block describes the relationship between differential collective pitch, airspeed and differential torque. This relationship is obtained with off-line simulations and is very linear. The output of the total system is a differential collective pitch signal. DTAS is only operative in airplane mode flight. Hence, in helicopter mode and conversion mode flight, it will generate no signal whatsoever.

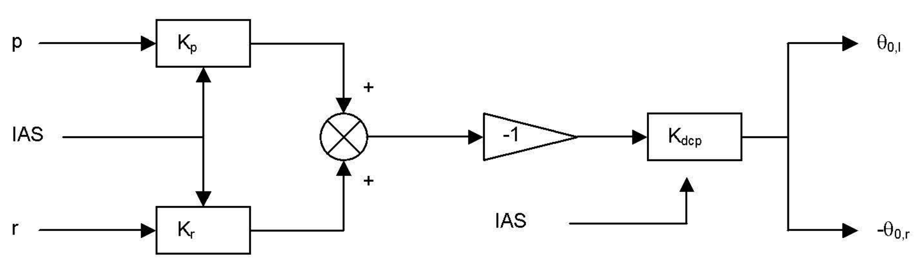

Figure 10: Differential Torque Alleviation System

Off-line simulations of pedal and lateral stick inputs performed with FLIGHTLAB ERICA model indicated that a loads reduction of approximately 90% can be achieved with this system in airplane mode! This is a very significant reduction. However, in actual flight, a combination of lateral stick and pedal inputs is frequently used. Also, it is not quite sure how the handling qualities of the aircraft are affected by DTAS. Piloted simulator trials therefore have to be performed.

Testing of the Differential torque alleviation system with piloted simulator trials

A number of piloted simulator trials have been performed in order to evaluate the influence of DTAS on handling qualities and to investigate the actual SLA. These tests are performed partly at the fixed-base Helicopter Pilot Station of the Dutch National Aerospace Laboratory NLR and partly at the full-motion helicopter simulator of the University of Liverpool. The DTAS-controller is tested by performing the roll-step mission task element (MTE) [ref. 10]. It is an ADS-33-like MTE [ref. 11], which is specifically designed for tiltrotor aircraft. This MTE is chosen for two reasons: firstly, because the structural loads on the interconnect drive shaft are likely to be at its maximum for this MTE; Secondly, the handling qualities of this MTE will be affected the most by DTAS. A number of test cases have been performed showing that the structural loads on the interconnect drive shaft are reduced by 90% for all cases. The torsion (twist) of the interconnect drive shaft for one particular test case is shown in Figure 11.

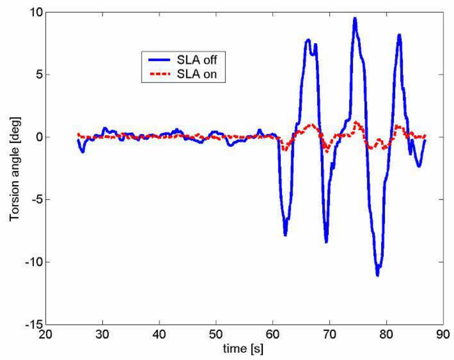

Figure 11: Twist angle of the interconnect drive shaft during the roll-step MTE at 210 knots forward flight in airplane mode

The ultimate load for the FLIGHTLAB ERICA model is achieved at approximately 75° of twist. So, without DTAS, the interconnect drive shaft is loaded up to 20% of its ultimate load, which is a very high fatigue loading. With DTAS, the shaft almost does not twist at all (maximum of 2% of its ultimate load). The test pilots gave handling qualities ratings for the MTE with and without DTAS. Their ratings are summarised in Figure 12.

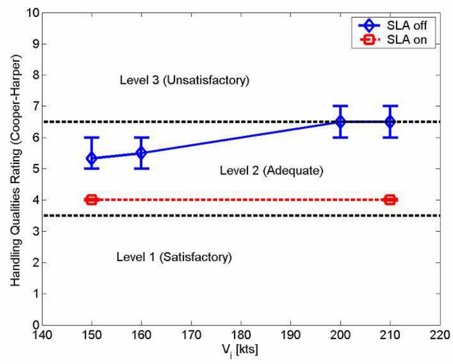

Figure 12: Handling qualities ratings for the roll-step MTE

One can see that the handling qualities ratings degrade from mid level 2 to the border of level 2/3 with increasing speed when DTAS is switched off. Two effects are present when increasing speed. On the one hand, higher roll rates can be achieved at higher speeds because the ailerons are more effective and thus it should be easier to perform the roll step (i.e. agility is enhanced). On the other hand, there is more workload required because there is less time to perform the manoeuvre at higher speeds and this will, of course, result in a degradation of handling qualities. Then, when the SLA controller is switched on, handling qualities improve to almost level 1 throughout the complete speed range. This is a very significant improvement. The differential collective pitch given by the system generates a proverse yaw effect. The pilot therefore does not have to give large pedal inputs anymore and workload is reduced a lot during the manoeuvre. One can say that it is a lot easier to perform coordinated turns.

<u>Structural Load Alleviation system design for the elastomeric flapping bearing</u>

Some theory about blade flapping is required before a SLA system can be designed to reduce steady-state blade flapping. The blade flapping motion may be represented by an infinite Fourier series:

$$\beta = a_0 + a_1 \cos\psi + b_1 \sin\psi + a_2 \cos 2\psi + b_2 \sin 2\psi + ... + a_n \cos n\psi + b_n \sin\psi \quad (1)$$

Where a_0 represents the average value, or coning angle; a_1 the longitudinal disc tilt angle w.r.t. the plane of no-feathering b_1 the lateral disc-tilt angle w.r.t. the plane of no-feathering;; $a_2....a_n$, $b_2...b_n$ second to higher harmonics in the Fourier series. Only the first three terms will be used in the subsequent analysis. Taking the derivative of flapping w.r.t. the azimuth and equating it to zero can derive the azimuth angle for which the maximal flapping angle is achieved. Substituting this azimuth angle in the flapping equation yields:

$$\beta_{\max} = \left| a_0 + a_1 \cos\left(\tan^{-1}\left(\frac{b_1}{a_1}\right)\right) + b_1 \sin\left(\tan^{-1}\left(\frac{b_1}{a_1}\right)\right) \right| \quad (2)$$

There is no structural difference for positive or negative flapping (that is why the absolute value of the flapping angle is taken).

The system to be designed has as goal to reduce the maximal steady-state flapping angle in forward flight. One would expect that there is only a longitudinal flapping angle in forward flight for tiltrotor aircraft. It is noticed however that the prop-rotor disks also have a lateral flapping angle in forward flight. The maximum steady-state flapping angle is therefore not obtained at ψ = 0° or ψ = 180°. This effect is present in all helicopter types and tiltrotor aircraft. The FLIGHTLAB ERICA simulation model uses a negative-δ_3 angle. A negative-δ_3 means that for every flapping up motion of the blade, the pitch angle is increased and thus the resulting air loads act to increase flapping. For sufficiently large negative values of δ_3, the lift load produced by is higher than the centrifugal spring force, which would try to decrease the flapping angle so that the rotor disk will then flap in the lateral direction due to precession. The coning angle and the hinge offset contribute as well to lateral flapping, however, they are minor factors compared to the δ_3-angle of the FLIGHTLAB ERICA simulation model.

The steady-state flapping reduction system designed is based on the fact that the main contributor of the maximal flapping angle is the longitudinal flapping angle. The longitudinal flapping angle can be reduced by an elevator deflection. For example, when the aircraft operates in conversion mode and the prop-rotor disk is tilted backward, then an elevator deflection can be given that causes a nose up pitching moment. The pilot will then have to give a forward longitudinal stick input to compensate for the nose up moment. The stick input will result in a longitudinal cyclic pitch input for the prop-rotors and thus reducing the maximal flapping angle. This basic principle is explained with Figure 13.

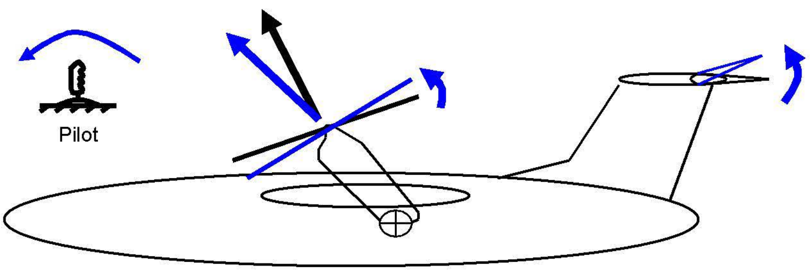

Figure 13: Basic working principle for the steady state flapping reduction system

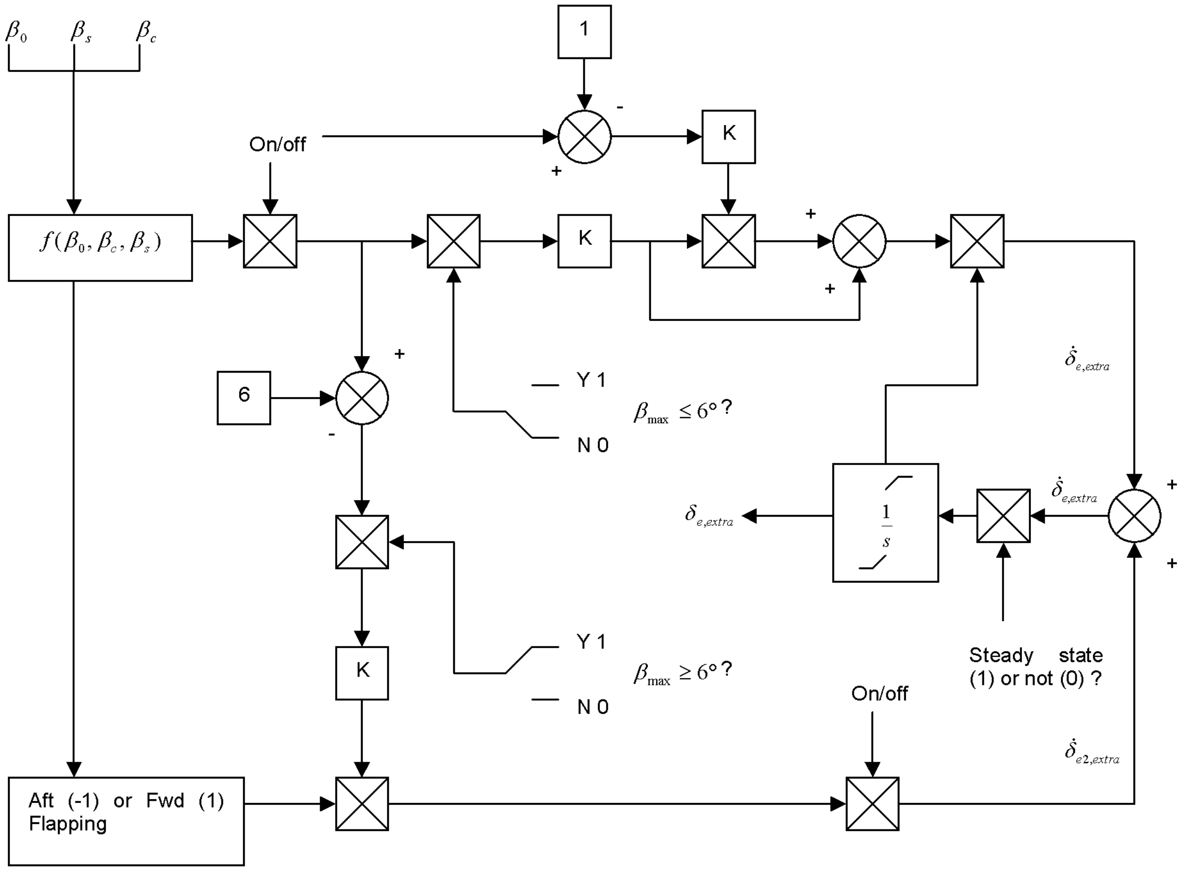

Figure 14: Steady-state flapping reduction system

This fairly simple principle is used to design the flapping reduction system in figure 14. The system as represented in Figure 14 works as follows: The elevator starts to deflect whenever the maximal flapping angle exceeds a certain limit. The longitudinal flapping of the prop-rotor disk is reduced by the elevator deflection. The maximal flapping angle is calculated from the coning angle, lateral flapping angle and longitudinal flapping angle. It is not just the maximal longitudinal flapping because the system is designed to protect the elastomeric flapping bearing. It could be that the maximal flapping angle encountered by the flapping bearing is higher than the maximal commanded flapping angle while the longitudinal flapping angle is still rather low. Reducing the longitudinal flapping can then still reduce the maximal flapping angle of the flapping bearing. For now, a flapping angle of 6° is chosen as maximal flapping angle. This is quite arbitrary but it implies that in the extreme case, a maximal flapping angle reduction of about 2° to 3° should be achieved by the system. The elevator deflection (δ_e) will be called an extra deflection angle ($\delta_{e,extra}$) because it is summed with the pilot commands. The aircraft will have a different trim condition due to this extra elevator deflection. When the trim condition is achieved with a maximal flapping angle of 6° then the elevator will not deflect anymore. The system will start to reduce the extra elevator deflection whenever the maximal flapping angle is smaller than 6°. For each flight condition there will be an optimal extra elevator deflection. The system will automatically find this optimum through the feedback of maximal flapping angle to the elevator. The rate of deflection ($\dot{\delta}_e$) is rather low, so the system will let the elevator oscillate gently around the optimal deflection angle. One can imagine that in some cases a large elevator deflection could be required. But a large extra elevator deflection might reduce the manoeuvrability of the aircraft significantly and it might be even dangerous. Therefore a limit has been set for the extra elevator deflection of ±10°. The complete elevator angle range of the FLIGHTLAB ERICA model is ±25° so this will leave enough control margin for the pilot. Turning the system off will cause the system to reduce the extra elevator deflection to 0°. This is done at a higher deflection rate than the normal deflection rates caused by the system. A higher deflection rate has been chosen because it would otherwise take too long for the elevator to return to its normal deflection. The system is designed to reduce the steady-state maximal flapping angle in forward flight but it must not influence any manoeuvres performed with the aircraft. Therefore the extra elevator angle is kept constant whenever the pitch rate, roll rate, yaw rate or roll angle becomes larger than 0.1 rad/s or when the roll angle exceeds 7°. A block is present in the system, which decides if the aircraft is in steady state. If not then it will multiply the rate of extra elevator deflection by 0. This block is not shown in the figure for the sake of clarity. The effectiveness of this system is examined in steady state trimmed forward flight. A trim sweep has been performed just like in Figure 6.

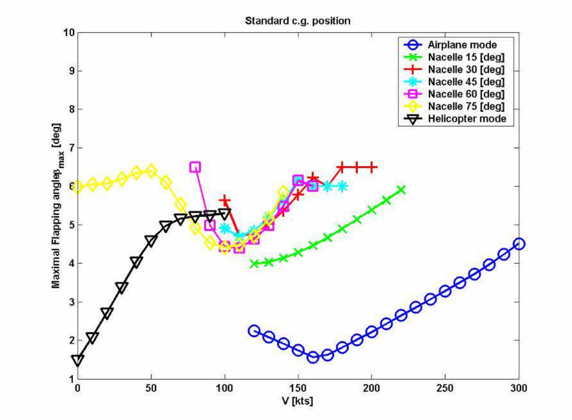

Figure 15: Trim sweep for the standard centre of gravity position with Flapping Reduction System operative

The maximal flapping angle is effectively reduced to 6° for most flight conditions by the system (see figure 15). In some conditions however it is only reduced to about 6.5° because the maximal extra elevator deflection is set to 10°. Reducing the maximal flapping angle to 6° is probably possible with greater extra elevator deflections. However this might affect the manoeuvrability of the aircraft too much. One can see that the longitudinal stick trim position is changed by about 10 % in some cases. This is significant but not objectionable. The system only reduces aft or forward flapping of the prop-rotor disks, while part of the maximal flapping angle comes from lateral flapping. The prop-rotors are counter-rotating; so opposed lateral cyclic pitch could be used to reduce the lateral flapping. This however is a recommendation for further studies. Changing the trimmed state of the aircraft will affect the drag of the aircraft and thus the power required. Results indicate that about 1-3% less power is required in the trimmed state with the flapping reduction system on due to the fact that the prop-rotors are directed more perpendicular to the free stream of the air. The prop-rotors will therefore work more efficiently and thus less power is required in the same flight condition with the flapping reduction system.

<u>Testing of the Flapping Reduction System with piloted simulator trials</u>

The philosophy of the flapping reduction system is that it will be continuously used throughout the complete flight envelope. The pilot will therefore never notice the presence of the system. The system will only affect handling qualities when it fails. To investigate this question, piloted simulator trials have been performed at the Helicopter Pilot Station of the Dutch National Aerospace Laboratory NLR. Four test cases are selected for the evaluation.

- Trimmed forward level flight, 80 knots IAS/ 60° nacelle angle/ Standard c.g. position
- Trimmed forward level flight, 160 knots IAS/ 60° nacelle angle/ Standard c.g. position
- Trimmed forward level flight, 180 knots IAS/ 45° nacelle angle/ Standard c.g. position
- Trimmed forward level flight, 200 knots IAS/ 30° nacelle angle/ Standard c.g. position

These cases were flown with 2 pilots (A and B). The flapping reduction system was switched on when the pilots had achieved a trimmed state and it was switched off again after they had achieved the trimmed state with flapping reduction system. Pilots were asked to give comments about the behaviour of the aircraft during the switching on and switching off. They were also asked to give comments about the new trim condition and about oscillations that might be introduced by the systems.

The aircraft behaviour is the same for all test cases except for the severity of the behaviour. A pitching-up moment is introduced when the flapping reduction system is switched on and it takes the pilots about three seconds to achieve the new trim state. Initially some height is gained due to the pitching-up moment. The power required in the new trimmed state is less than with the system switched off. The new pitch attitude is almost exactly the same as before. Switching the system off causes a nose down pitching moment and the original trim state is achieved again after pilot corrections. So the aircraft loses height after switching off the system due to the nose down moment. The difference between the four test cases is the severity of the pitching behaviour. The maximal flapping angle is higher at a higher flight speed and thus the flapping reduction system commands a greater elevator deflection to reduce the maximal flapping angle. This combined with greater dynamic pressure results in a greater pitching moment.

The pilots commented that they were hardly able to notice the difference in trim conditions and they did not think that the FRS introduced oscillations. The pitching moment introduced when switching the system on or off was perceived to be very significant at high-speed flight and it was perceived to be mild at low speed flight.

Normally a system like this is active throughout the complete flight envelope and thus only switching off transient is interesting because the system might fail sometime. After failure it generates a pitching down moment so the height loss should not be too large. The response of the aircraft for the case at 200 knots with nacelles set at 30° for pilot A after switching of the system is displayed in figure 16. This case is the most extreme case. Also the flapping angle reduction is shown and the elevator commands of the system.

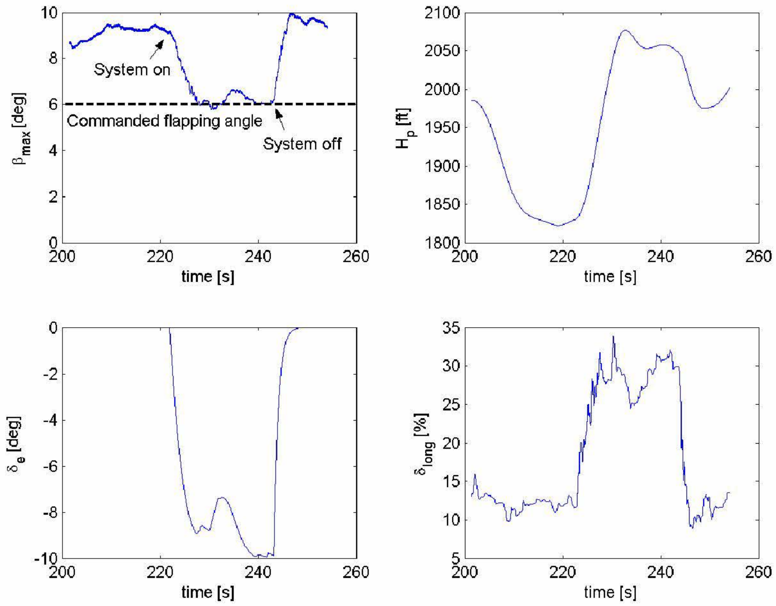

Figure 16: Testing of the Flapping Reduction System in the NLR Helicopter Pilot Station

It can be seen from Figure 16 that the maximum flapping angle is effectively reduced to approximately 6°. The FRS commands an elevator deflection of almost 10°. The pilot counteracts the pitching moment caused by the deflection by pushing the stick forward. About 200 feet in height is gained during the switching on phase of the system. Switching the system off results in opposite behaviour of the aircraft and pilot, which could be expected. The height loss is about 75 feet during the switching off phase. This height loss is smaller than the height gain because the pilot knows how large the pitching moment is going to be which he/she has to counteract. It is recommended that a warning system is present in the cockpit to inform the pilot when the system fails because height loss can be dangerous when operating close to the ground.

Conclusions

The goal of the present paper was to develop SLA solutions particularly for alleviating the critical loads on two components of the tiltrotor propulsion system, i.e. the interconnect drive shaft and the elastomeric flapping bearing. Off-line simulations with the FLIGHTLAB ERICA Tiltrotor Simulation model developed in the frame of ACT-TILT have been performed to investigate the critical loads. These simulations gave the following results:

- Yaw rate and Roll rate in airplane mode cause a large load on the interconnect drive shaft. The load is also highly dependent on airspeed. It has never appeared in literature that a yaw rate has a significant effect on the load.
- Steady state flapping angles are high for high speed and low speed conversion mode flight. This results in a high fatigue loading of the elastomeric flapping bearing.

Two SLA have been designed: the differential torque alleviation system (DTAS) and the steady-state flapping reduction system (FRS). The following results are obtained with DTAS system:

- A loads reduction of 90% is achieved for the ADS-33 roll step MTE, which is the most critical MTE for the interconnect drive shaft with respect to loads and handling qualities.
- Handling qualities are improved from borderline level 2/3 to borderline level 1/2 for the roll step MTE due to a proverse yaw effect given by DTAS

The following results are achieved with the FRS system:

- Steady-state flapping angles are reduced effectively for the critical flight conditions.
- Power required in those flight conditions is less because the rotor disks are oriented more perpendicular to the airflow.
- The system has no effect on handling qualities

Recommendations for further work

- DTAS is only operational for airplane mode flight. The system should be expanded so that it will work throughout the complete conversion corridor.
- DTAS should be tested for all ADS-33 mission task elements that are relevant to the civil-tilt rotor missions.
- The FRS only reduces longitudinal flapping of the rotor disks. Opposed lateral cyclic pitch could be used to reduce the steady-state lateral flapping as well
- It is indicated in open literature that transient flapping angles can get very high during manoeuvres. These transient flapping angles should also be reduced.

Acknowledgement

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