Flight Director for Slung Load Handling
- First Experiences on CH53 -

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Abstract. This paper describes the concept and the flight test results of flight director for helicopter with slung load. The flight director gives the pilot a convenient aid to effectively damp the load pendulum motion and to allow manoeuvring without exciting oscillatory load modes. Swinging helicopter external slung loads often lead to dangerous situations which not only can result in a total loss of the transported load itself but also can endanger the safety of the helicopter and its crew. The development and flight test results of a demonstrator system on the DLR BO105 are outlined. Further, the architecture of a slungload flight director system for the large cargo helicopter CH53 is described and preliminary flight test results are shown.

1 INTRODUCTION

In last decades helicopters are increasingly used for humanitarian aid and disaster relief missions. These missions include also the operation with external slung loads. Figure 1 shows as an example a CH53 helicopter with an underslung water bucket in a fire fighting mission.

Figure 1: *CH53 on a fire fighting mission*

In flight, helicopter, cable and load form a two body pendulum system with main degrees of freedom in the longitudinal and lateral direction. Additional load modes e.g. in pitch and yaw direction can couple into the pendulum modes. Especially, for aerodynamic effective loads with a natural yaw damping a coupled yaw - lateral pendulum mode can occur which is only marginally damped.

The pendulum modes can be excited by helicopter manoeuvring (e.g. acceleration, deceleration and turns), aerodynamic disturbances and pilot control action. Swinging helicopter slung loads often lead to dangerous

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situations which not only can result in a total loss of the transported load itself but also can endanger the safety of the helicopter and its crew.

In dependence of the mass and slung length, the pendulum motion of the external load normally leads to a feedback on the helicopter dynamics. The pilot senses this feedback as disturbances of acceleration, velocity and attitude and intuitively tries to compensate by corrective inputs. An additional complicating factor is that the pilot cannot directly see the slungload. The lack of appropriate cues aggravates the situational awareness. The fact that often the strategy for effectively damping load oscillations is not clear, in many cases, the corrective inputs do not damp the load pendulum motions but even excite them.

An additional issue is that during a slung load mission the pilot as a controller is in a high gain loop for stabilizing the load pendulum motion or even stabilizing an exact geo-referenced position. The pilot workload is increased and for long lasting mission pilots fatigue becomes a critical factor. The lesser the pilots experience or training level on slungload operation is, the more aggravate the situation becomes.

To give the pilot a practical aid for actively damping slung pendulum oscillations and therewith increasing safety and convenience for external slung operations, DLR proposed the use of a flight director. A flight director is a common used means in flight control to provide the pilot in his function as a "controller in the loop" with appropriate predictive information. The indicator works as a command instrument and takes over part of the pilot's control task resulting in a reduced pilot workload. However, control authority remains at all times in the hands of the pilot.

A flight director demonstrator system for the DLR BO105 was developed in cooperation with IMAR, a manufacturer of inertial measuring systems, and several flight test campaigns were conducted starting with aerodynamically stable loads and ending up with loads showing only marginal stability properties, prone to a coupled lateral-yaw limit cycle oscillation. Reference [1] and [2] give a comprehensive overview of the trials and the very positive pilot ratings of DLR and non-DLR pilots. Basing on these results the development of a slungload flight director system for the German Army CH53 was started. A simulation environment for the CH53 was developed and preliminary flight test with cargo bridges were conducted [3], [4]. At the moment, flight tests trials with marginally stable loads are carried out. This paper briefly describes the flight director principal functionality and the preceding BO105 flight tests. The paper then focuses on the flight director system developed for the CH53 helicopter. Preliminary results of the on-going CH53 flight test campaign will be shown.

2 FLIGHT DIRECTOR

The helicopter slung load flight director uses an indicator display similar to a regular artificial horizon and is arranged as additional instrument located in the pilot's field of view. Figure 2 shows the demonstrator display at the left hand pilot side in the BO105 helicopter. Several load pendulum motion quantities are measured and processed. From this data, the flight director identifies the right damping strategy and generates predictive commands which are displayed as additional horizon deflections (i.e. distortions) in pitch and roll. The correct damping strategy considers the introduction of longitudinal and lateral accelerations at the upper slung attachment point by helicopter pitch and roll motion.

Figure 2: *demonstrator system on BO105*

The pilot treats the deviations as flight dynamic disturbances and intuitively compensates them with corrective inputs. This automatically leads to the correct helicopter motion for damping of the load pendulum motion. The control strategy for compensating artificial horizon deflections and the control authority, remain always in the hand of the pilot. For manoeuvring the pilot controls the helicopter such that the flight director display indication is brought into correspondence with the desired flight attitude. The manoeuvre then is conducted without excitation of the load pendulum mode. The pilot's workload is remarkably decreased, whereas situational awareness increases.

The advantage of the flight director approach for slung load damping is that the functionality is independent of the slung configuration (e.g. cable length, mass) and the pilot retains always full control authority.

3 PRECEDING INVESTIGATIONS ON BO105

As a proof of concept, flight test trials with a stable and an only marginally stable load have been conducted on the DLR BO105 demonstrator helicopter. The system was extensively tested and evaluated by DLR pilots and non-DLR pilots. For the final system assessment tests, a specially tailored body which incorporated an oscillatory lateral pendulum /yaw tendency within a particular speed range was used (Figure 3).

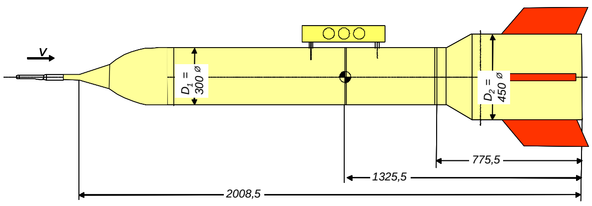


Figure 3: *BO105 marginally stable load*

3.1 Lateral pendulum / yaw mode

The body itself normally has sufficient aerodynamic directional stability with respect to its centre of gravity (whether cock stability). However, when hooked up to a cable, a coupling between the load body yaw degrees of freedom and the pendulum lateral degrees of freedom occurs. The coupled mode is only marginally damped and might develop a lateral pendulum-yaw limit cycle of finite amplitude. This is also known as the endangering and feared large amplitude fish-tail motion when transporting aerodynamic effective loads under a helicopter. From an eigenvector analysis of this mode it can be seen that the yaw and lateral-pendulum motion are perpendicular to each other and, interestingly, the mode can not be stabilized by increasing the vertical surface since it does not change the 90° phase shift between the yaw and lateral pendulum motion [2], [5].

The effect has been theoretically investigated using a non-linear simulation model for the load depicted in Figure 3. Results for the influence of cable length on the stability properties of the lateral pendulum / yaw mode (green symbols) and a higher frequent oscillatory yaw mode (blue symbols) at 60kts (30m/s) forward speed are shown in Figure 4(a). In the second pane the red dotted line indicates the reference pendulum frequency which is obtained by:

$$\omega_0 = \sqrt{\frac{g}{l}\left(1 + \frac{m_{load}}{m_{helicopter}}\right)} \quad , \quad T_0 = \frac{2\pi}{\omega_0} \tag{1}$$

The frequency of the lateral / yaw mode almost exactly follows the reference frequency. However, the damping is only marginal and even negative for short cable lengths. The relative damping ratio reaches about 2% for 15m of cable length.

Further, the influence of forward speed on the lateral-yaw mode is shown in Figure 4(b). It can be seen how the lateral-yaw mode arises from a coalescence of the pure body yaw and the pure lateral pendulum mode at low forward speeds. The mode is instable until ~15 m/s and only marginally stable for speeds >15 m/s. Apart from the cross over region, the period stays constant and corresponds well with the reference value. The damping of the yawing mode stays constant for speeds >5 m/s. Its period decreases with forward speed.

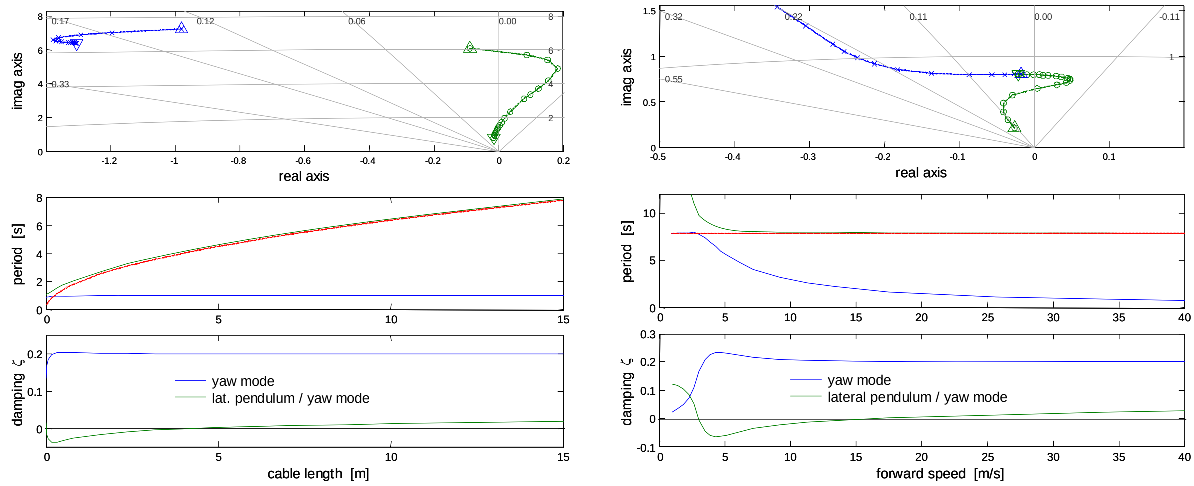


Figure 4: *lateral modes in dependence of cable length (a) and forward speed (b)*

Due to non-linear aerodynamic effects for larger amplitudes the simulation predicts that this mode is prone to develop a limit cycle with a finite amplitude. This effect could be confirmed by flight test [2].

3.2 BO105 flight test results

BO105 flight tests were performed at 60kts (30m/s) with a cable length of 15m (Figure 5). The safety pilot excites the load pendulum motion with slight roll inputs at 60kts. The evaluation pilot takes over control and uses the flight director in order to actively damp and stabilize the load motion. All pilots flying the unstable slung load had extensive BO105 experience. They used the BO105 agility and control power to follow the flight director commands.

Figure 5: *DLR BO105 with unstable load*

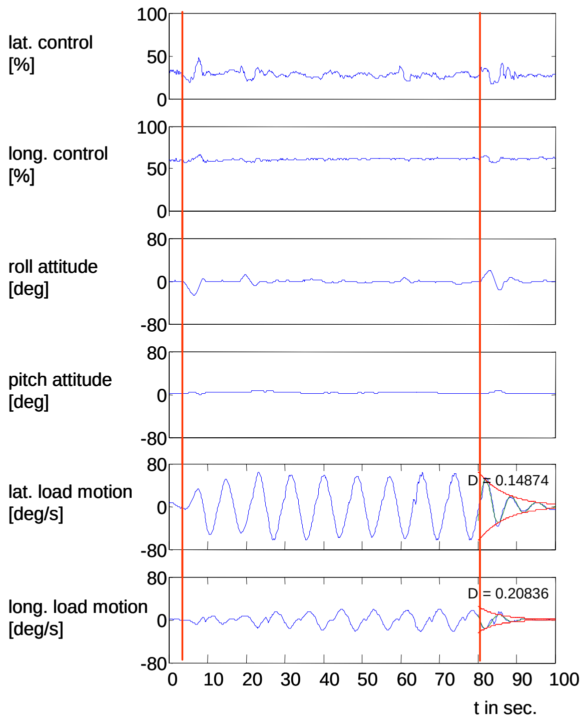


Figure 6: *unstable load motion damped using the flight director*

Figure 6 shows exemplary a roll excitation by the safety pilot. A lateral limit cycle oscillation occurs with high amplitudes. Load lateral attitude reaches 70°. The longitudinal mode slowly diverges without the pilots exciting it. Pitch oscillations arrive at ±20° of amplitude.

After about 75 seconds the evaluation pilot starts with his corrective control inputs. With only one 20° bank doublet manoeuvre he manages to effectively damp the high amplitude limit cycle, within one cycle. Also, the damping of the longitudinal mode is impressive. Most impressive for the pilot is that he sees the load disappearing out of his side window within one cycle which he mentioned to be 'a very reassuring feeling'.

After some training, the pilots could achieve damping ratios comparable to the stable load case. Using the flight director, the load can be handled at any time without any problem. Even in the moderate forward speed regime (20 - 40kts) where the lateral mode was identified to be instable large amplitudes up to 70° could be effectively damped. A transition from forward speed to hover could be made without any problems.

4 CH53G FLIGHT DIRECTOR SYSTEM

Basing on the experience with the demonstrator for the BO105 helicopter a flight director system is developed by IMAR for use on the CH53G. Focus of the new system was the use under operational conditions. Especially, the power supply and the load sensor concept have been redesigned.

4.1 Flight director system architecture

The flight director system developed by IMAR for the CH53G consists of a measuring section, a processing section and a display section. The measuring section has to acquire the load position and rates as well as the helicopter attitudes. This leads to a system architecture which on the one hand requires an IMU (inertial measurement system) together with integrated AHRS (attitude heading reference system) functionality and high bandwidth to measure helicopter states. On the other hand, an appropriate sensor to determine the slungload motion. Regarding the slungload sensor, two different concepts have been investigated, developed and flight tested.

First, the acquisition of load states can be performed by a second IMU, fix-mounted at the sling cable at some point below the helicopter. This second IMU measures the angular rates. Together with an appropriate coordinate transformation, the full motion of the payload regarding to the helicopter coordinate system can be determined. For the rate sensing, micro mechanic MEMS technology is used which provides the desired results. Many flights have been performed successfully with this double-IMU configuration. Nevertheless, this installation requires a separate power supply (batteries), an accurate continuous referencing between the two IMU coordinate systems regarding heading (e.g. with magnetometers mounted on both sites) as well as a wireless data transmission. Also the sling mounted IMU could be damaged or lost during emergency load disconnection or during an emergency landing.

Due to these disadvantages, an alternative solution which does not require any installation outside the fuselage was developed. The key for the advanced solution is the small-size low-power image tracker, which has been developed in the past for several kinds of vehicle tracking applications. Advantage of this miniaturized tracker is a quite high processing rate, which allows also tracking objects with high accuracy. In comparative flight tests the latter solution showed considerably more operative potential and was therefore selected for succeeding flight tests.

4.2 Image Processing

A panoramic field-of-view camera is mounted at the helicopter cargo hook shaft looking directly down on the slungload (Figure 7). In order to have a clear trackable object, a special marker is fixed on the load sling in approx. 3 to 6m below the cargo hook. The marker is coated with a contrast painting to be easily detectable by the image tracker. Optionally, an active marker can be used containing infrared light emitting diodes (IR-LEDs). This way, it is also visible under dark or low contrast conditions.

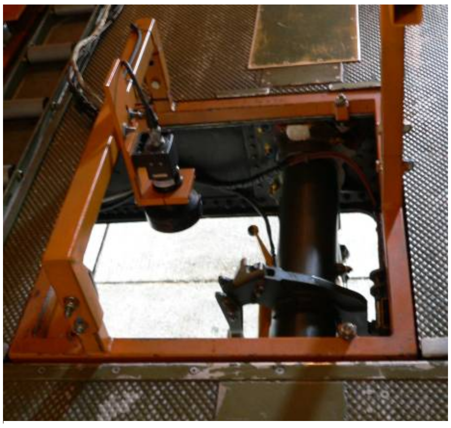


Figure 7: *camera in cargo hook shaft*

The data from the camera are fed into the image tracker electronics. The image tracker contains several enhanced image processing algorithms, running on a high density free programmable gate array (FPGA). The algorithms are able to perform fast correlation calculations and to apply an adaptive gradient filtering. The result of the image processing is the pixel coordinates of the marker. These data were scaled with calibration data obtained from a camera calibration procedure performed at system manufacturing. Such, the measurements are a metric representation of the location of the marker in helicopter coordinates with sub-pixel accuracy. The positions are transformed to load pendulum angles and rates.

The image processing includes a data validation process, which is used to visualize the pilot whether the process performs proper tracking or whether it has lost the marker for any reason. The alarm time for detectable mismatches is less than 0.1 seconds. In those cases, the watchdog of the algorithm starts a new search of the marker to assure that the marker will not remain un-tracked. The re-tracking only takes a few seconds assuming that the marker is in the field of view under the appropriate conditions.

The measurements of the image tracker and the data of the stand-alone helicopter mounted IMU/AHRS are merged in a data fusion algorithm running on a separate micro-controller unit

Figure 8: *flight director display in CH53G cockpit*

(MCU). The command outputs for the flight director display are computed and transmitted to the display mounted in the cockpit directly in the field of view of the pilot (see Figure 8). The command display is generated on a PDA hand held computer, showing the regular attitude indicator. In default mode, helicopter attitudes are indicated and the command display runs parallel to the basic helicopter attitude indicators. In flight director mode, additional commands are superimposed on the displayed attitudes.

Figure 9 shows all the flight director components as mounted on the CH53G. The AHRS / IMU providing the reference helicopter states is mounted in the cargo bay, the camera in the cargo hook shaft and the PDA display in the cockpit. The image tracker is mounted, preferably close to the cargo hook. The flight director algorithms are running on a processing unit integrated in the image tracker housing. Image tracker, IMU and the PDA display need a low voltage DC power supply. For data transfer camera, image tracker and IMU are cable connected, whereas the PDA has a blue tooth data connection to the image tracker. Finally, the whole system is certified according German military aviation regulations.

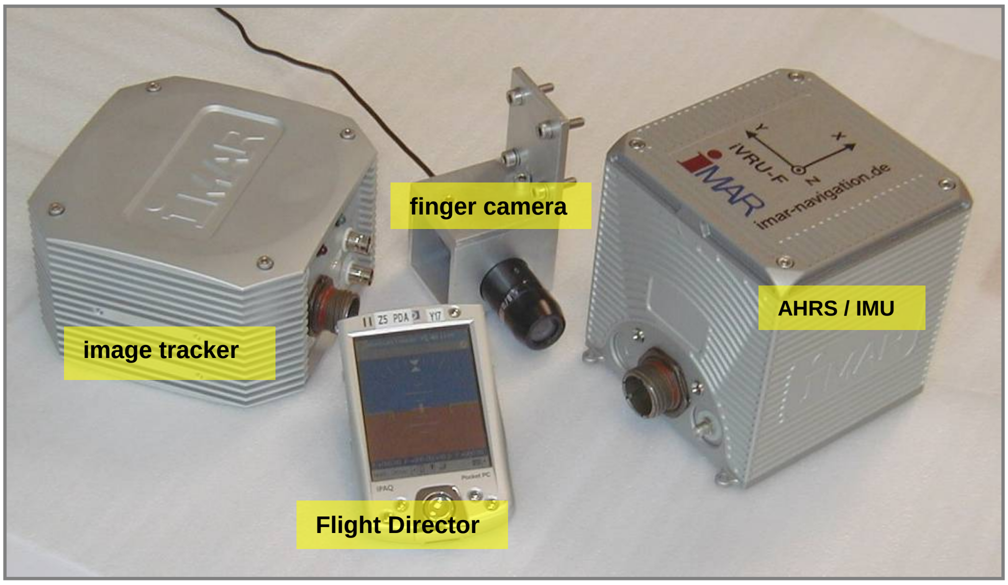


Figure 9: *flight director system for CH53G*

4.3 Simulation

The control strategy of the overall system has been tested and optimized on several levels. First an offline simulation has been used to verify the algorithms and to test the “look & feel” behaviour with several pilots. The PC-based simulation helps the pilot to understand the philosophy behind the flight director and helps him to establish the right command following strategy. Experiments showed that after a few minutes an unskilled pilot is able to correctly recover large pendulum oscillations. Further tests have been performed on the piloted simulator at DLR showing similar convincing results.

5 CH53G FLIGHT TESTING

The slungload flight director system is now flight tested under operational conditions on the CH53G large cargo helicopter of the German Army. The tests take place at the WTD61 large flight test facility in Manching. Again, two different types of loads: one being a 4 metric tons concrete block, i.e. aerodynamically stable, the other being a fuel drop tank, only marginally stable (see Figure 10), are used.

Figure 10: *marginally stable load CH53*

5.1 CH53 marginally stable load

Similar to the BO105 marginally stable load, a CH53 load body with a mass of about 2500kg has been tailored for present task. The original body was used as an external fuel drop tank on the Tornado fighter. The tank has an overall length of about 6.5m and a maximum diameter of about 0.8m. For the tests, the body will be filled with water. At the top the tank features 2 hooks. An adapter is manufactured which fits in between the two hooks and provides several eyes for the attachment of the sling harness. The front and aft sling cable join in a single point about 2 meters below the cargo hook. The overall length of the sling harness for this load is about 12m.

In contrast to the BO105 aerodynamic effective load body, the CH53 load is not provided with stabilization fins (vanes). As predicted from theory, the load will now turn itself perpendicular to the flow. For higher forward speeds a lateral pendulum / yaw mode builds up. Interestingly, lateral pendulum motion and yaw motion again have a 90° phase shift, however, the sign is of opposite sense. Now, the lateral motion is ahead of the yaw motion.

5.2 Phase lag

To assess the performance of the system with respect to latency times and required lead shaping a stability consideration is made. Since slungload damping more or less deals with one discrete frequency a simplified consideration at this particular frequency only is assumed adequate. Figure 11 gives a schematic representation of the overall lateral damping system including the helicopter dynamics, the load dynamics, the flight director system and, finally, the pilot closing the loop. Helicopter lateral dynamics directly influence the load dynamics. These dynamics are sensed and by the flight director algorithm translated into commands on the flight director display. In this leg sensor latency times and lead shaping characteristics of the flight director algorithm play an important role. Finally, following the cues from the command display the pilot controls his helicopter in the roll axis.

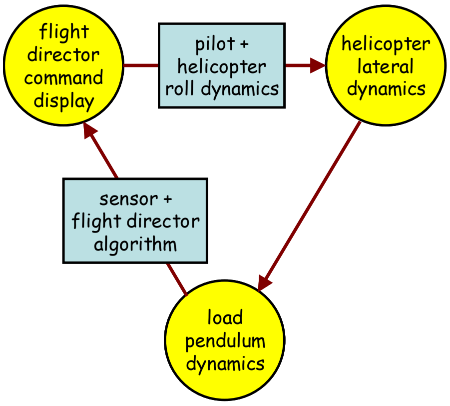
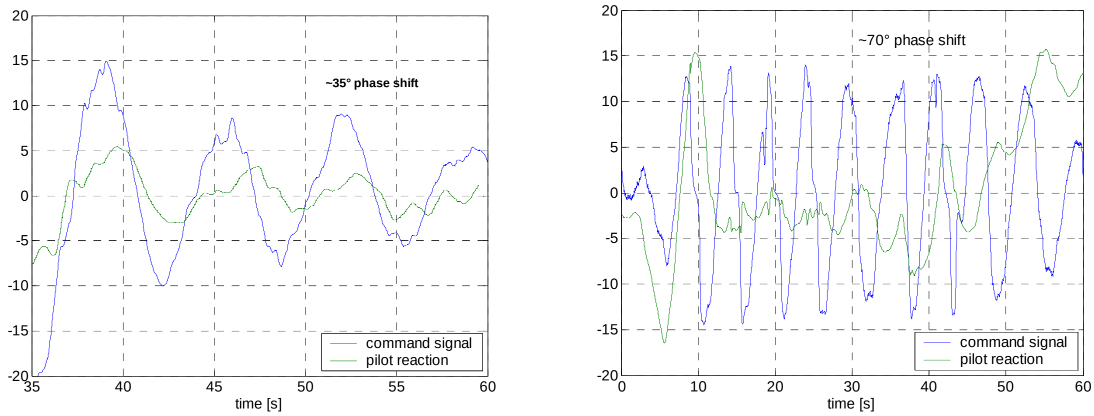


Figure 11: *schematic representation of slungload lateral damping loop*

From BO105 flight tests, the overall phase margin was assessed by incrementally adding time delay to the system and letting the pilot rate when the system becomes instable. The results showed an approximately 20° of overall phase margin at the particular pendulum frequency of about 0.8rad/s. In flight test, this was found sufficient robust in the whole speed regime for different pilot control strategies.

Any additional delay reduces the existing phase margin. Two positions were identified where differences in time delays between BO105 and CH53 can occur: 1) the command following performance in the pilot / roll dynamics leg, i.e. how fast the pilot can follow his commanded cues and 2) at the sensor unit, i.e. how much latency time the sensor and the processing unit produce. Both aspects have been investigated more in detail.

First, the command following performance derived from BO105 flight test cases is compared to data of a command tracking task on the CH53. Figure 12 shows the results for both cases: blue lines denote the commanded signal while green lines symbolize the pilots following performance. In both cases experienced pilots were performing the task. The phase shift between the two curves is obtained by a curve fitting optimization routine. The phase shift on BO105 is determined to be about 35°, whereas on CH53 about 70° were computed. These are realistic numbers bearing into mind the differences in agility of the hingeless BO105 helicopter in comparison to the large cargo helicopter CH53.



(a) BO105 *(b) CH53*

Figure 12: *comparison of command following performance*

Second, Table 1 gives an overview of the latency times of the different sensor and processing components. The image tracking unit as used on the CH53 shows about 15ms more latency time in comparison to the AHRS solution of the BO105. In terms of phase shift this means a variation of about 1° at the corresponding pendulum frequency. In comparison to the phase shift resulting from the pilot command following, the sensor phase shift can be neglected.

Device	Latency	Resolution	Comments
AHRS	5 ms	< 0.05 deg	200Hz data rate
image tracker	< 20 ms	< 0.1 pixel	coordinate level
processing unit and command display	< 3 ms	-	computation and display

Table 1: *flight director system specifications*

In order to remain stability with a phase margin of ~20°, however, a lead shaping algorithm, providing about 35° of lead becomes necessary. A special designed algorithm is implemented on the processing unit can provide phase lead of up to 45°, which should give enough phase reserve to ensure a stable operation. The length of the sling between load and helicopter is always dimensioned such that the pendulum frequency is low compared to the helicopter's dynamics. Consequently, the limits of this self-adaptive estimation process show a more theoretical character. The algorithm will be tested during the upcoming closed loop CH53 tests.

6 CONCLUSIONS

A flight director for slungload damping has successfully been implemented and tested on a BO105 helicopter. Even marginally stable loads could easily be handled. The slungload flight director therewith contributes to a safety increase in slungload operations.

The system is adapted for further testing on a CH53G helicopter of the German Army. Several modifications have been made to meet the operational requirements. System performances with respect to latency times have been assessed in comparison to the BO105 system.

An assessment of the expected stability margins for the CH53 helicopter has been performed using experiences from the BO105 flight tests. Due to larger command following phase shifts, the CH53 system needs additional lead shaping elements in the flight director loop. Appropriate algorithms have been implemented and will be flight tested with the upcoming closed loop CH53 slungload test trials.

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