FLIGHT DIRECTOR FOR HANDLING OF HELICOPTER SLING LOADS

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Abstract

This paper describes the analytical investigations which have been performed in preparation for flight testing of a flight director for helicopter with sling load. The flight director developed at DLR 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 sling 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 flight director was flight tested on DLR's BO105 using mainly two different types of external load: a relatively heavy tree log with a basic stable behaviour and a relatively light aerodynamic effective body with only marginal stability properties prone to a coupled lateral pendulum-yaw mode. The analysis base on a non-linear dynamic and aerodynamic load model developed for these investigations.

Introduction

In the past decades helicopters played an important role in the transportation of heavy and bulky loads from and to inaccessible places or places where other means of transportation are not practicable. In the recent past an intensification of this role could be observed not only for military operations but also in humanitarian and disaster relief missions (see Figure 1).

For helicopter sling operations the load is hooked up to helicopter cargo hook by a sling cable. The helicopter and its load form a two body pendulum system which characteristics depend on a variety of parameters, e.g. sling cable length, number of slings, load aerodynamic behaviour and helicopter/load mass ratio. In dependence of these characteristics the system can be prone to weakly damped oscillatory or even instable pendulum modes.

Figure 1: CH53 fire fighting mission

The pendulum motion can thereby be induced by helicopter manoeuvring (e.g. acceleration, deceleration and turns), aerodynamic excitations (disturbances, gusts) and pilot excitations. Swinging helicopter sling 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.

When the coupled dynamic system of helicopter and load is in danger of getting out of control the pilot can be forced to premature release the endangering load which in most cases leads to its total loss. An even worse scenario occurs when parts of the load or the sling cable strike the main or tail rotor disk which almost inevitably leads to a fatal loss of the helicopter. Several recent incidents and accidents underline the potential danger of helicopter sling operations. Accident investigations show that only 2 oscillation periods can be sufficient to excite a sling load such, that cable or load strike either main or tail rotor disk.

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In order to give the pilot a practical aid for actively damping sling pendulum oscillations and therewith increasing safety and convenience for external sling 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.

In this context a demonstrator system for the DLR BO105 was developed. Two flight test campaigns were conducted to evaluate the functionality of the sling load flight director. In the flight test trials two different type of external loads were used: 1) a relatively heavy tree log with a basic stable behaviour and 2) a lighter aerodynamic effective body with only marginal stability properties, prone to a coupled lateral-yaw limit cycle oscillation. Both loads are tested with a single point attachment. For better understanding the first load will be referred to as "stable load", the latter as "unstable load". Test and results for the stable load trials were described in reference [1], whereas reference [2] gives a comprehensive overview of the trials with both stable and unstable external loads in which also non-DLR pilots participated. At present a flight test campaign for the evaluation of the sling load flight director on a CH53 of the German Army is under preparation.

Many theoretical studies have been performed to better understand the dynamic behaviour of towed bodies in general and the coupled helicopter load system behaviour in particular. In [3] the stability of an aerodynamic effective towed body is investigated. Special emphasis was put on the appropriate modelling of the elastic sling cable between finned body and towing aircraft. Lateral instabilities where found to be an inherent property of aerodynamic effective or finned bodies with whether cock stability. In reference [4] a sling and load simulation model is presented which also tries to count for cable torsion effects. In [5] the non-linear coupled dynamic system of helicopter and load is analysed using bifurcation theory. As one result of these investigations stable and unstable helicopter/load configurations could be determined. Other investigations focus on the effect of the suspended load on helicopter stability and handling qualities. Results presented in ref. [6] indicate that lateral load modes can couple into the helicopter Dutch roll mode decreasing its damping. Load mode frequencies are generally to low to influence the helicopters bandwidth and phase. Reference [7] shows that a high load to helicopter mass ratio can drive the lateral phugoid instable. Further studies were conducted to develop advanced handling qualities criteria for slung operations using both simulator and flight test trials. Ref. [8] and [9] focus on the assessment of handling qualities for cargo and utility helicopters, whereas [10] compares simulation and flight results for a UH60 Black Hawk helicopter with slung load. In [11] Bell 412 dynamics and handling qualities are compared for an internally and externally carried 2600 lb load. The results show that for special cases the stability and handling qualities are slightly better when carrying the load externally.

The present paper focuses on the theoretical investigations that have been performed in order to prepare for the 2004 DLR BO105 flight tests with stable and unstable load and for the CH53 flight tests scheduled for the end of 2005. The principal functionality of the sling load flight director is briefly outlined as well as the results of the performed flight tests and the preparations for the oncoming CH53 test campaign.

Sling Load Flight Director

In dependence of the mass and sling 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 can not directly see the sling load. The lack of appropriate cues aggravates the situational awareness. In combination with 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 will, in contrast, even excite them.

To provide the missing cues often mirrors are attached at the front to the fuselage. Also load position indicators (e.g. cross pointers) find application for sling load operations. Another possibility is that additional members of ground- or flight crew give information on load position and motion by radio. In addition they can give instructions for corrective inputs to damp oscillations or to position the load. All these methods, however, require a high level of qualification and experience of pilot and crew.

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 additional flight director display at the left hand pilot side in the BO105 demonstrator. 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 (i.e. the helicopter cargo hook) by helicopter pitch and roll motion.

Figure 2: cockpit arrangement of experimental flight director display in BO105 demonstrator

The pilot treats the deviations as flight dynamic disturbances and more or less intuitive compensates them with corrective inputs. This automatically leads to the correct helicopter motion for damping 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 is conducted without excitation of load pendulum mode.

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

Simulation Models

In order to optimally prepare for the flight test the sling load dynamic behaviour has to be well understood. A simulation environment was developed which incorporates non-linear models for the load and sling cable dynamics and aerodynamics. The cable is attached to a towing point which basically performs a steady state forward motion. However, also open loop dynamic manoeuvres, such as climb/descent, acceleration /deceleration or turns can be performed.

The cable is modelled as a spring damper system without mass. Cable forces only result from the independent relative motion and distance between the towing and load attachment point. The cable cannot produce any negative spring forces. This can lead to a load bouncing motion when strong vertical manoeuvres are introduced at the towing point.

The load itself is modelled as an independent 6 degree of freedom rigid body with mass and inertia. The equations of motion are evaluated in a body fixed coordinate system. The external driving forces and moments are the cable force and the aerodynamic forces and moments.

The cable force is introduced in the attachment point which generally is not identical with the body centre of gravity.

Aerodynamic forces and moments can be obtained from table look-up in dependence of body angle of attach and angle of side slip. As a second option a generalised model for cylindrical shaped bodies is available. This model calculates non-linear lift and drag in dependence of flow angles, flow stall effects and Reynolds number. Also the destabilising Munk-moment is taken into account. In addition to the core aerodynamics also vertical and horizontal fins can be considered. For each of the fins the local aerodynamic states are evaluated. The resulting flow angles are corrected for aspect ration and the so called '2-α-effect'. This effect occurs for fins or blunt wings on a body in a non-axial flow. The flow around the body causes local velocity deviations and therewith consequently flow angle chances. The fins themselves are represented as flat plates with small aspect ration. For the fins, also, stall effects are taken into account.

Finally, all forces and moments are summed in the body CG. In an integration step the rigid body motion is evaluated.

The load configuration parameters are set in a configuration table. A trim procedure calculates the rigid body states which cope with the predefined initial conditions. For stability analysis the model is linearised with respect to the trim point.

Due to the high cable spring and damper constants the system tends to be stiff. Simulation is therefore performed with an appropriate integration scheme which accounts for both accuracy and performance.

Flight Test Campaigns

Flight director evaluation flight test campaigns on the BO105 helicopter with the stable and unstable load took place at the beginning and end of 2004. A third test campaign with a CH53 of the German Army is presently under preparation. The flight tests are scheduled for the end of 2005. The previously used unstable load is modified for these tests. Its mass is increased from 50kg up to ~200kg, mainly to reduce the resulting pendulum amplitudes.

All three campaigns were accompanied by preparatory analytical investigations of the respective load dynamics. For this, the simulation environment described before was setup for the particular load configuration. Simulations and stability analysis were performed to gain more insight in the load dynamic behaviour. Especially weakly damped or even instable modes eventually developing stable limit cycles were of interest. The next chapters will briefly describe the particular flight test campaigns and discuss more into detail the results of the preparatory investigations.

In the next figures the root locus of the investigated modes in dependence of a parameter of interest is shown for various cases in the upper pane. The upward pointing triangle indicates the starting position, whereas the downward pointing triangles mark the end position. The period and relative damping ζ of the modes of interest are shown in the middle and bottom pane. ζ=0 indicates no damping and for ζ=1 the mode becomes aperiodic.

BO105 stable load For safety reasons the first flight test trials were performed with a stable load. A tree log proved to be best suited for these tests. It has no noteworthy aerodynamic instabilities and a natural damping coefficient in lateral direction for 60 kts forward flight of $\zeta \approx 0.07$ as identified from flight test.

The tree log is hanging in a vertical position, the sling attached to the upper end. Basic key parameters are: mass $m = 410\ kg$, body length $l_b = 6\ m$ and radius $r = 0.22\ m$. The unextended cable length is $l_0 = 15\ m$. Due to its high density the aerodynamic forces are relatively small in comparison to gravitation and inertia forces.

The middle pain in Figure 3: shows the calculated damped lateral and longitudinal oscillation period. It is very close to the theoretical reference value estimated with:

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

which is indicated as a red dotted line in the middle pane.

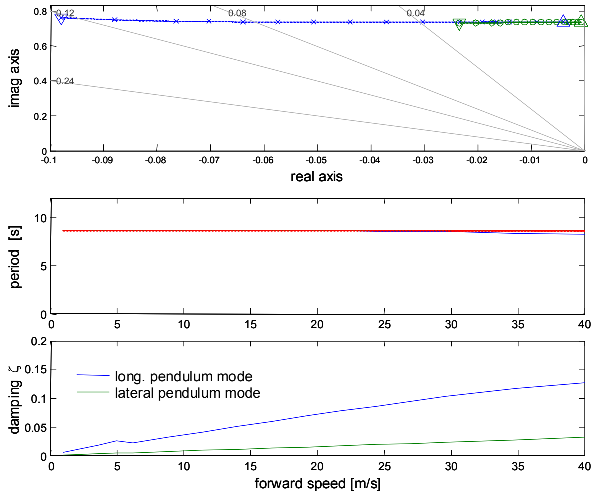

Figure 3: lateral and longitudinal modes in dependence of forward speed

The longitudinal damping increases with forward speed, whereas the lateral damping stays marginal. For hover both modes are practically undamped. The predicted lateral damping of $\zeta \approx 0.02$ at 30ms (~60kts) is lesser than the damping identified from flight test. The longitudinal damping comes close to the flight test value.

In this baseline case no further (weakly damped) modes of interest could be observed. All other modes are either well damped or are at uninteresting high frequencies.

During the test campaigns it was observed that some pilots tried to damp the load oscillations by flying smooth turns or accelerated climbs. It was tried to reproduce the effects of these strategies in simulation.

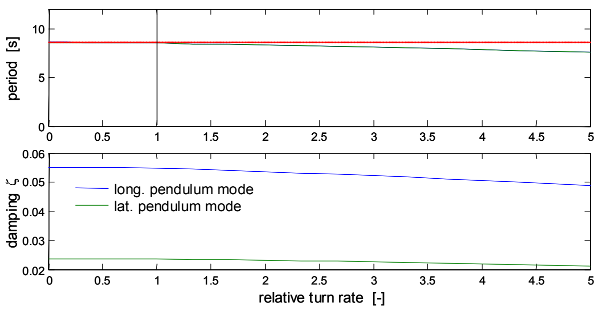

Figure 4: period and damping for turn rate variation

Figure 4 shows period and damping in dependence of the relative turn rate. The reference turn rate is the standard 2-min-turnrate at 3°/s. As can be seen the steady turn has almost no effect on damping. The same result was obtained for accelerated climbs. Both manoeuvres, in fact, increase the virtual gravitational acceleration which is equivalent to a load mass increase. Damping and pendulum period are not much influenced. However, the resulting amplitude is reduced.

In conclusion the investigations did not produce any particular recommendations for the flight test.

The flight tests were performed with DLR pilots and later on repeated with non-DLR pilots in the scope of a workshop. As an example Figure 5 shows the results of the active damping using the flight director. Between the two red lines the lateral and longitudinal modes are exited by helicopter roll manoeuvres. Then, the pilot starts actively damping the pendulum motion using the flight director. The pilot manages to damp the pendulum motion within 2 periods. The periods of the occurring oscillations compare well with the simulation results. The roll damping with flight director is much increased in comparison to the baseline case.

Pilots were very impressed of the performance of the system. They managed to damp stimulated load oscillations within 2 or 3 periods. Also they were able to fly quite aggressive manoeuvres without exciting pendulum motion

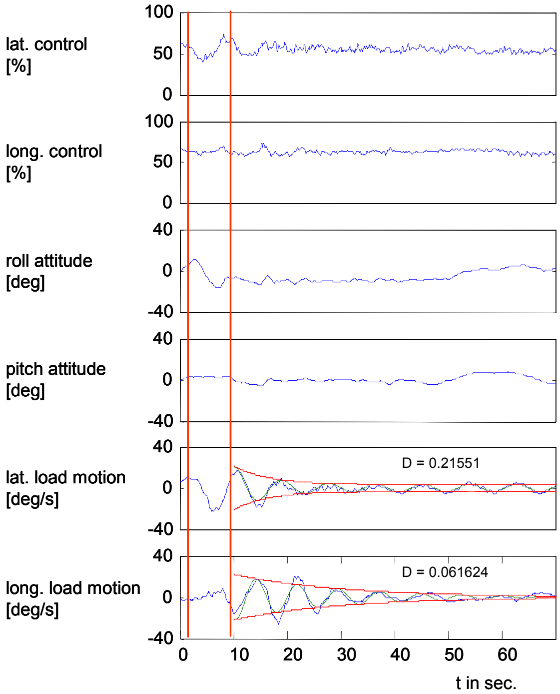

Figure 5: slung load damping with flight director

BO105 unstable load As a proof of concept flight test trials with a only marginally stable load were conducted at the end of 2004. Figure 6 shows the specially tailored body which was used for these tests incorporating an oscillatory pendulum tendency within a particular speed range. The mass of the body $m \approx 50\ kg$.

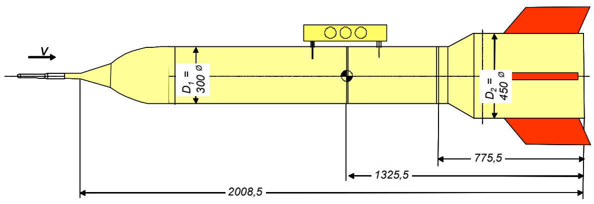

Figure 6: unstable load (all measures in mm)

For this kind of external loads an interesting effect could be observed when analysing the lateral motion. 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, couplings between the body degrees of freedom and the cable degrees of freedom can occur, which might lead to instability of small perturbations. From these instabilities a lateral pendulum-yaw limit cycle of finite amplitude can develop. This is also known as the endangering and feared large amplitude fish-tail motion when transporting aerodynamic effective loads under a helicopter.

To analyse the phenomenon investigations start with a body configured as shown in Figure 6, however, fixed in its CG position. Thus, only roll, pitch and yaw degrees of freedom remain. Figure 7 shows the yaw and pitch stability for a 30 m/s forward speed. In the reference case both modes are stable and show a period of ~1s.

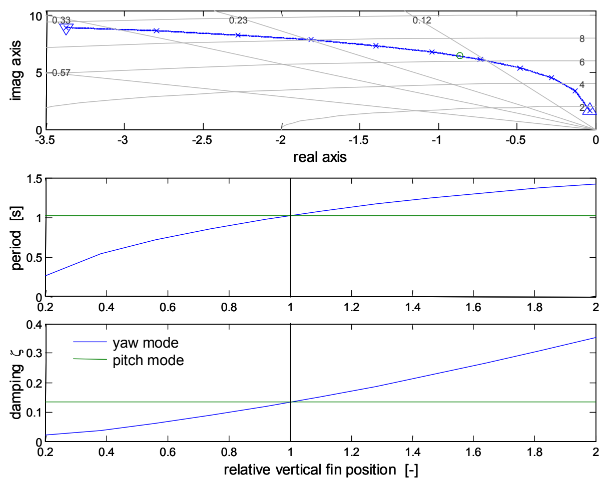

Figure 7: pitch and yaw modes in dependence of relative vertical fin position

Yaw stability can be further increased when the vertical fin is moved away from CG and decreased when moving the fin towards CG. When putting the fin at the CG location the yaw mode becomes a-periodic divergent due to the destabilising Munk-moment. As shown in Figure 8 the same behaviour can be observed when varying the vertical fin surface.

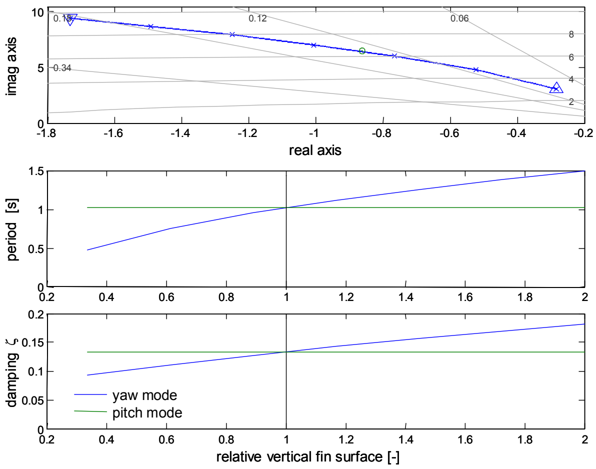

Figure 8: pitch and yaw modes in dependence of relative vertical fin surface

So far, both described phenomena express the basic understanding of aerodynamic stability.

The next step is to connect the body to its attachment point, ~0.25*m* above CG, and vary the cable length from $l_0 = 0\ m$ to $l_0 = 15\ m$. Again, forward speed is fixed at 30*m/s*.

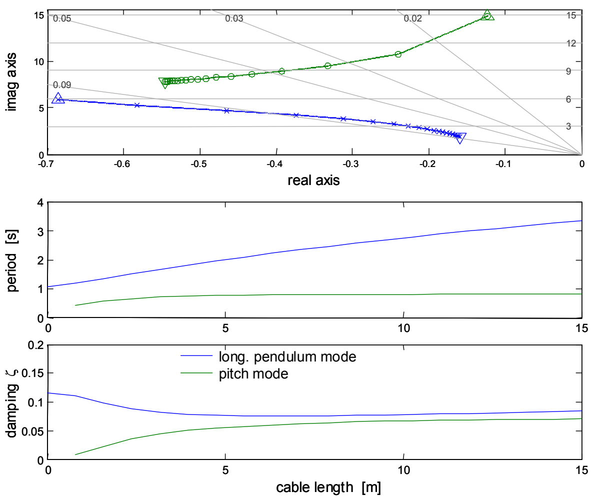

Figure 9: longitudinal modes in dependence of cable length

As can be seen from Figure 9 a longitudinal pendulum mode develops as well as a pitching mode about the attachment point. The modes are not coupled. The pitching mode is comparable to the pitching mode from Figure 7. Both modes are weakly damped. The pendulum mode corresponds to the longitudinal mode as shown in Figure 3, although the period is less the reference pendulum period (see eqn.1) for the particular cable length.

Figure 10 shows the lateral modes in dependence of cable length. A yawing mode, similar to the one in Figure 7, with the same period but slightly lesser damping, occurs. Interestingly, a coupled lateral pendulum-yaw mode is existent. The mode is identified as an interaction of yawing degree of freedom and lateral pendulum degree of freedom. Due to its typical combination of yaw and pendulum motion this mode is also called the fish-tailing mode.

The period almost exactly follows the reference pendulum period, depicted as the red dotted line in the middle pane. However, its damping is only marginal and even negative for short cable lengths. Therefore, the cable length should be well adapted when flying these kinds of external loads.

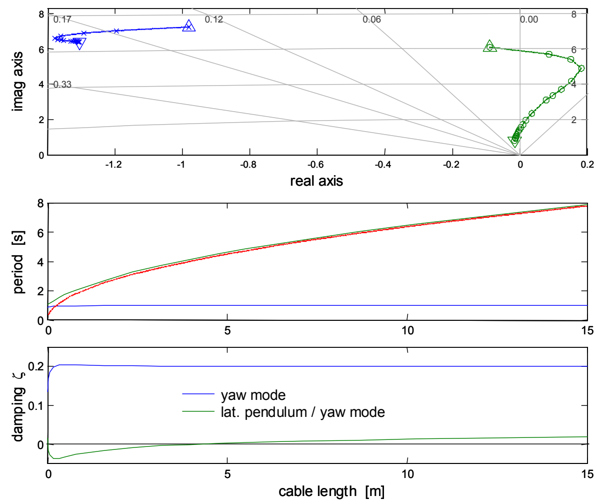

Figure 10: lateral modes in dependence of cable length

Since the damping, however, even for longer cable lengths, is only marginal this mode is prone to develop a limit cycle with larger amplitudes. The 15m cable configuration is therefore further investigated. Simulation runs have been performed to analyse the effect of the aerodynamic non-linearities for larger amplitudes. As an example Figure 11 shows the time history of the pendulum lateral angle (represented by the body roll attitude) and the yaw angle (i.e. heading). A left pendulum attitude and a right yaw attitude are positive. After a lateral disturbance at t=0 a very low damped convergent oscillation develops. The yaw motion shows a 90° phase shift compared to the lateral motion, leading to the characteristic fish-tailing motion property. The frequency is close to the one obtained from the stability investigations with the linearised model. A high frequent oscillation about the body's symmetry axis is sampled on the low frequent lateral oscillation.

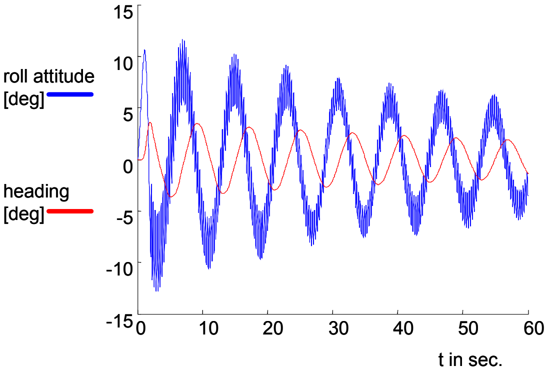

Figure 11: lateral pendulum-yaw motion, marginally damped

Further stability investigations were performed to study the effect of forward speed on the longitudinal and lateral modes. Figure 12 shows the results for the longitudinal modes. As for the stable load the damping is practically zero for hover. The period of the pitch mode decreases with forward speed. Its damping has a maximum at ~15*m/s*. The damping of the pendulum mode increases steadily with forward speed. In hover and slow forward motion its period corresponds well with the reference value, indicated as red dotted line. However, starting from ~15 *m/s* the period reduces to about half the value of the reference case.

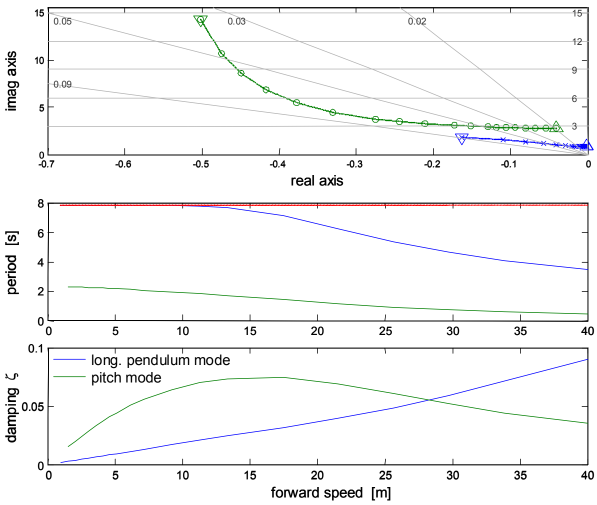

Figure 12: longitudinal modes in dependence of forward speed

For lateral modes some interesting effects occur as can be seen from Figure 13. At low forward speed the yaw mode crosses over the lateral pendulum mode causing the appearance of the coupled lateral pendulum-yaw mode. 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.

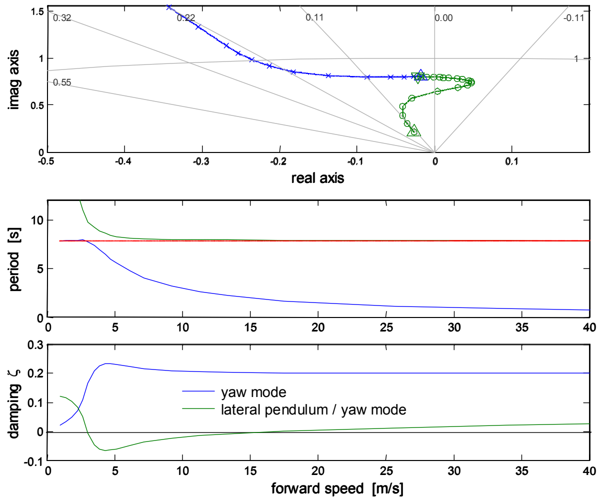

Figure 13: lateral modes in dependence of forward speed

Figure 13 learns that extreme care has to be taken when reducing forward speed, especially, when already a lateral pendulum motion has built up at forward speeds of e.g. 30 m/s. A lot of energy could be transferred into the motion causing extreme amplitudes.

In order to overcome the low speed instability it was investigated how the vertical fin position and surface could be tailored in order to better damp the lateral pendulum motion.

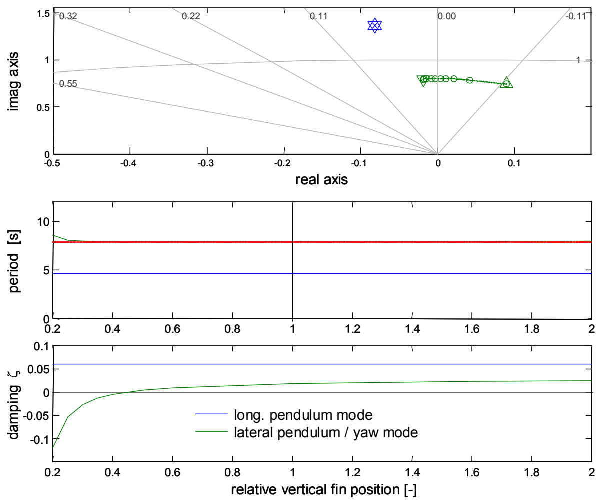

Figure 14: longitudinal and lateral pendulum modes in dependence of relative vertical fin position

Figure 14 shows the effect of varying the vertical fin position with respect to its reference position on longitudinal and lateral pendulum motion. The longitudinal mode is not influenced by the vertical fin position, at all. The lateral period is not influenced, either. Unfortunately, the lateral damping can not substantially be increased by putting the fin further backward. In contrast, the damping can be decreased, and even can become negative, when reducing the fin effectiveness, i.e. putting it closer to CG. The same result was obtained for the fin surface. It is thus, not possible to substantially increase lateral pendulum damping by vertical fin modifications.

The explanation is that the fin side force drives both, lateral and yaw 'sub-motions' in the coupled lateral pendulum-yaw resonance mode. Phase shift is such that energy is fed from yaw into the lateral pendulum motion. The amount of side force only affects the amount of energy transferred and therewith the resulting amplitudes. However, it has no effect on the 90° phase shift between the two sub-motions which is mainly responsible for the instability.

Interestingly, this phenomenon is completely in contrast with the results for the CG fixed body as shown in Figure 7 and Figure 8. Since, here is no coupling between the lateral and yaw motion, the lateral damping could be influenced by vertical fin position and surface variations.

Above investigations show that the lateral pendulum-yaw mode becomes instable when the fin lever arm is reduced to about half the reference surface. For this configuration, again at 30*m/s* and 15*m* cable length, non-linear simulations have been performed.

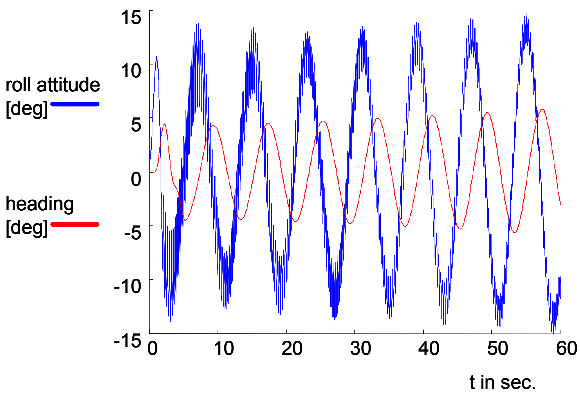

Figure 15: lateral pendulum-yaw motion divergent limit cycle

Figure 15 shows the time history of the pendulum lateral angle (represented by the body roll attitude) and the yaw angle (i.e. heading). Again, a left pendulum attitude and a right yaw attitude are positive. After a lateral disturbance at t=0, now, a divergent limit cycle is initiated. The yaw and lateral pendulum motion again show a 90° phase shift. For intermediate values of fin position a stable limit cycle could be observed.

From these studies three conclusive recommendations for the succeeding flight tests could be drawn:

- extreme care should be taken when familiarising with load, since it is prone to lateral pendulum motion and might develop a limit cycle with large amplitudes
- use a cable length > 10m to avoid inherent lateral instabilities
- avoid as much as possible the low speed regime when transitioning from forward speed to hover

DLR pilots performed preliminary flight tests to familiarise with the unstable load (Figure 16). A 15*m* cable was used. At 60kts the load initially behaved fairly stable but could be brought into a lateral pendulum-yaw limit cycle by slight lateral disturbing inputs. When slowing down the amplitudes of the limit cycle could reach ±70° of lateral deviation. These results qualitatively confirm the conclusions of the analytical investigations.

Figure 16: DLR BO105 with unstable load

After the familiarisation tests the flight director system was installed and flight tests with DLR pilots were performed. Later on they were repeated with non-DLR pilots in the scope of a workshop.

To perform the test the safety pilot excites the load pendulum motion with slight roll inputs at 60*kts*. The evaluation pilot takes over control and uses the flight director in order to actively damp and stabilise 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 17 shows 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.

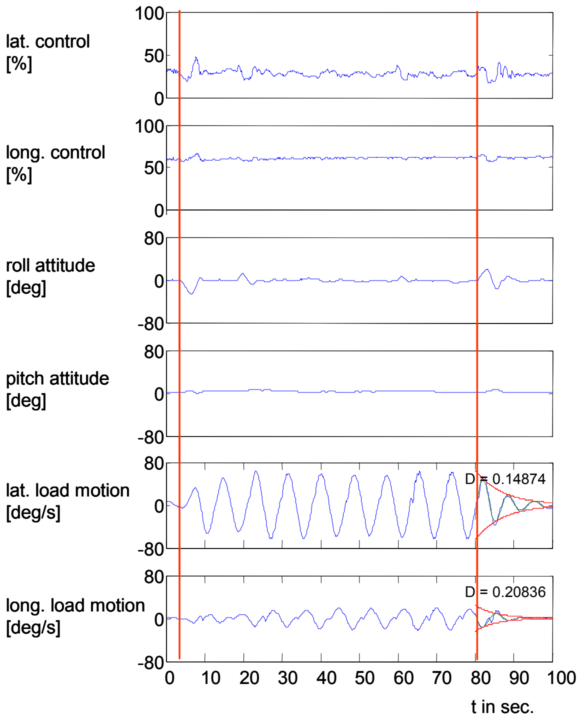

Figure 17: unstable load motion damped using the flight director

After about 75 seconds the evaluation pilot starts with his corrective control inputs. With only one single 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. The flight tests with DLR and non-DLR pilots (Eurocopter, WTD, LBA) showed that when using the flight director the load can be handled at any time without any problem. Even in the moderate forward speed regime (20 - 40*kts*) 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.

CH53 unstable load As a further proof of concept flight test with a CH53 of the German Army are scheduled. The tests will take place at the WTD61 flight test facility in Manching and should demonstrate the applicability of the flight director for heavy cargo helicopters and also demonstrate the independence of the flight director concept of helicopter type.

CH53 tests will also start with a stable load first. Since, however, no big differences in dynamic load behaviour in comparison to the BO105 tests with a stable load are expected only the unstable load will be addressed here.

To better adapt to the CH53 dynamics and not let the load to helicopter mass ratio drop to much it was decided to increase the mass of the aerodynamic body from 50kg to about 200kg. This mainly reduces the effective resulting amplitude.

As a side effect, however, the fins are now too weak to support the body and prevent it for roll over at take off and landing. Therefore, the lower vertical fin is removed and replaced by a supporting bracket (see Figure 18) which fixes roll attitude when the body is on ground.

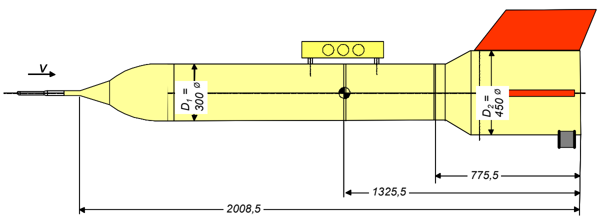

Figure 18 a,b: modified unstable load

To avoid instabilities due to the reduced effective vertical fin surface as described in the preceding subchapter the surface of the upper fin was enlarged by a factor of 2.5. This means that the total fin surface, now, is 1.25 times larger than before.

For this configuration with the enlarged upper fin again stability investigations at 30*m/s* and 15*m* cable length have been performed. Figure 19 shows the effect of mass variation. The longitudinal mode becomes faster for increasing mass and asymptotically approaches the reference period. However, the damping of both modes is drastically reduced. The lateral mode is only marginally damped for the 200*kg* body.

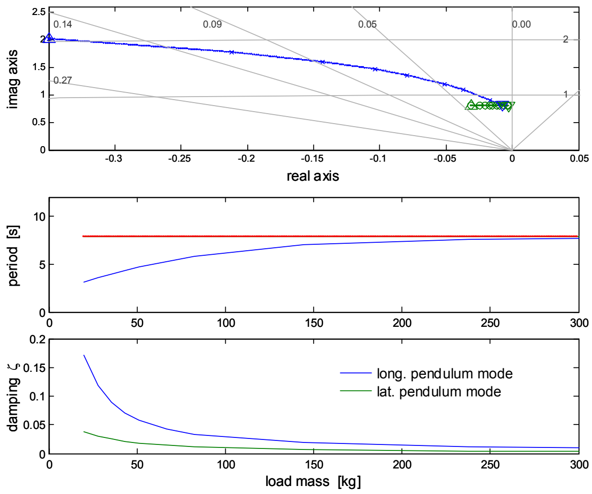

Figure 19: longitudinal and lateral pendulum modes in dependence of mass

A first idea was to further increase the vertical surface. From Figure 20, however, it can be seen that no increase of damping can be achieved by this measure. The load configuration is expected to be very prone to a limit cycle motion.

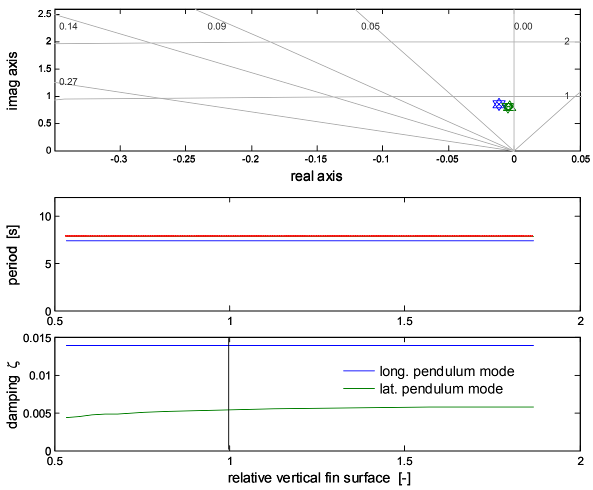

Figure 20: longitudinal and lateral pendulum modes in dependence relative vertical fin surface

In a final non-linear simulation the expected limit cycle is investigated. Figure 21 shows the time histories of the pendulum lateral angle (represented by the body roll attitude) and the yaw angle (i.e. heading) for the 30*m/s*, 15*m* cable, 200*kg* mass, removed lower fin and enlarged upper fin configuration.

After a lateral disturbance at t=0, a stable, slightly damped limit cycle with finite amplitude develops. The yaw and lateral pendulum motion again show a 90° phase shift. Simulated amplitudes are in he same order of magnitude as the ones for the BO105 unstable load.

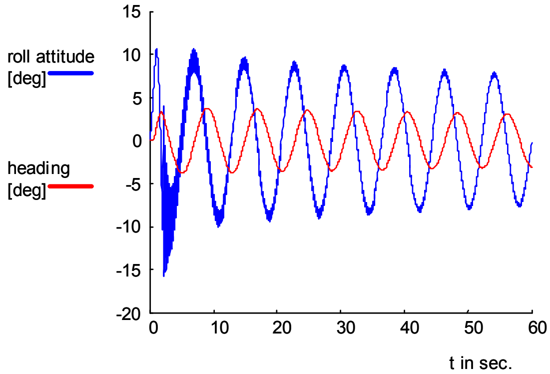

Figure 21: lateral pendulum-yaw motion stable limit cycle with finite amplitude

The conclusion that can be drawn from the CH53 unstable load investigations is that the lateral damping is further reduced by increasing the load mass. Fortunately, however, the developing limit cycle is expected to behave well and to show finite amplitudes.

Therefore, the recommendations for the oncoming CH53 flight director flight test campaign are similar to the ones for the BO105 campaign:

- take extreme care when first familiarising with the load. The load is prone to lateral pendulum motion and might develop a limit cycle with large amplitudes
- use large cable lengths: ≥ 15m. This avoids inherent lateral instabilities and reduces the pendulum period which gives the pilot more time to react
- avoid as much as possible the low speed regime when transitioning from forward speed to hover and vice versa.

Finally, Figure 22 shows the new setup of the flight director system. In contrast to the BO105 system the new system, features a portable PDA to display the flight director instrument. The PDA can be located at the pilot's knee or mounted at free spot in the helicopter cockpit. All communication is performed wireless by the Bluetooth protocol.

Figure 22: flight director system for CH53 flight test campaign

Summary

A flight director for helicopter with sling load was presented which provides the pilot with an effective and comfortable aid for external load operations. The flight director contributes to the increase of safety for this kind of operation. Flight tests with a demonstrator system for the DLR BO105 to assess and evaluate the potential of the flight director have been successfully conducted with DLR and non-DLR pilots. Two test campaigns, one for stable and one for unstable loads have been performed. A third campaign on a German Army CH53 is scheduled for the end of 2005.

In preparation for the test campaigns a non-linear simulation environment was developed to allow stability analysis and non-linear simulation of the helicopter sling load dynamics. The non-linear sling load model takes account for all relevant aerodynamic effects. Especially, the effects of several load configuration parameters on the predicted lateral pendulum-yaw limit cycle were investigated. From the investigations recommendations and precautions for the succeeding flight tests were derived. All of the predicted effects could, at least qualitatively, be observed in the first two flight test campaigns.

The oncoming CH53 flight test campaign requires several load modifications from an operational point of view. Again, the simulation environment was used to investigate the low damped pendulum modes for this configuration and to derive recommendations for the conduction of the tests. The simulation environment, therewith, is a very valuable tool in preparing for helicopter sling load flight director tests campaigns.

Outlook

As a proof of concept at the end of 2005 flight test with a CH53 of the German Army are scheduled. These tests should demonstrate the applicability of the flight director for heavy cargo helicopters and also the independence of the flight director concept of helicopter type.

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