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DYNAMIC PROBLEMS OF UNMANNED TETHERED ROTOR PLATFORM SEA-KIEBITZ WITH SPECIAL REGARD TO THE LANDING

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INTRODUCTION

Unmanned tethered rotor platforms differ in their dynamics from manned helicopters of the same size because of the strong influence of the tethering cable on the dynamic behaviour of the system.

Dornier has developed such a platform system, the operational Kiebitz, which will soon be ready for multiple production.

In the case of using tethered rotor platforms on a ship as for example the SEA-KIEBITZ (fig. 1), a modified form of the operational Kiebitz, further dynamic problems arise from the movement of the ship which causes strong disturbance of the system of tethering cable and Kiebitz at low altitudes. Based on a brief explanation of the system, its structure, its function, and its equipment the standard mission phases are analysed.

The main flight characteristics of the system are described in these phases. The operational limits of the system will be shown and explained. Possible ways to realize an optimum system configuration are discussed, with special regard to the landing.

THE SEA-KIEBITZ SYSTEM

The SEA-KIEBITZ system comprises (fig. 2):

- Carrier and radar
- Tether cable and winch drum on deck
- The deck landing pad with protecting cover
- Airborne unit monitoring and control panel
- Radar Control and Display unit. Radar information may also be presented on ship's tactical display

Fuel supply and data to and from the carrier and radar are provided via the tether.

The carrier is a rotor supported platform with torque free blade tip drive and an automatic flight control system.

The platform is controlled in a fashion similar to a helicopter in pitch and roll and by deflection of turbine exhaust gases in yaw. The cable tension is automatically controlled by using the collective pitch and by the power management of the turbine.

The SEA-KIEBITZ can be operated from the small landing platforms of non aviation ships or FPBs in moderately high seas.

SEA-KIEBITZ with a special radar is capable of almost tripling the radar horizon of current ships and of extending their surface surveillance capability by almost ten times (fig. 3).

The performance of current on board missile guidance or target detection equipment is severely limited by the height of masthead aerials.

The strike range of medium range missile systems is therefore limited.

Thanks to its mission height of 300 metres, the SEA-KIEBITZ extends the radar horizon to approximately 60 km or 35 n

For example, a FPB equipped with SEA-KIEBITZ will be able to overlook the entire sea area of the Western Baltic from coast to coast.

SEA-KIEBITZ with for example a FERRANTI SEASPRAY radar could provide 24 hour surveillance over the horizon even in adverse weather conditions without the problems of a data link, and readily integrates with existing ships' weapons systems.

SEA-KIEBITZ may be deployed from ships and also from those vessels that are too small to support a helicopter, and greatly enhances their offensive capability.

Some specifications of the carrier and the radar are listed in fig. 4.

The main supposition for all SEA-KIEBITZ activities was to use the carrier of our operational KIEBITZ without changes in its hardware and the structure of the controller if possible.

MAIN MISSION PHASES

The main mission parts of a SEA-KIEBITZ operation from a ship are

- rotor start
- take-off and ascending to mission heights of about 300 m, pulling up the tether cable by a controlled tether tension
- surveillance at mission altitude for 24 hours maximum
- hauling down and landing on the deck
- rotor stop

Analysing these operations the environment in which they take place must be considered. The problems created by the motion of the ship and its landing platform (which may be very restricted in size), the relative wind and the air turbulence around the ship must be discussed in relation to their effect on the performance of the platform.

In relative wind from ahead, the airflow around the ship and its superstructure in the vicinity of the landing platform, is variable and complex in character and depends on the type of ship. It has not yet been considered for the landing cases analysed here because too few data were available.

DYNAMICS OF THE SYSTEM

As said before unmanned tethered rotor supported platforms are differing in their dynamics from manned helicopters of similar size because of the strong influence of the (tensioned) tethering cable. Because of their configuration and their flight performances required by their cargo as for example special radars, tethered helicopters drones like the KIEBITZ can be looked at in some other way as manned helicopters.

Only a few dynamical aspects of the SEA-KIEBITZ shall be presented here with special regard to the landing. Because it is there that the actual problems of tethered rotor platforms operated from moving vehicles arise.

Fig. 5 shows three time histories of simulated SEA-KIEBITZ flights at a mission height of 300 m. The system is disturbed by a horizontal headwind step gust of 5 m/sec at the beginning of the flights. The comparison of the uncontrolled tethered and untethered flight may show the strong influence of the tensioned cable. The pitch attitude time history of the untethered flight shows the normal oscillatory divergent long term response of the hovering helicopter. The curve of flying tethered under the same assumptions shows a similar initial pitch response of the platform. But after about 1,5 sec the tension force of the tether cable increases and declines according to the tether cable curve. It forms a pitch moment and tries to turn back the helicopter against the gust-induced pitch up rotor moment.

The most important and characteristic factors that determine the dynamics of the SEA-KIEBITZ-tether cable system are the own natural frequencies in the rotatorial and translatorial axes of the helicopter, ω_{rot} and ω_{tr}, especially under consideration of the ship's pitching, heaving and rolling. ω_{tr} is much more critical than ω_{rot} because of the ship's roll mode at moderate sea state. The cause is that the ship can roll with the same frequency - and usually ships roll at their own natural roll frequency - as the own natural translatorial frequencies of the SEA-KIEBITZ are. This is the case when the drone is hauled down and approaches the deck to a distance of only a few meters for landing-on, or if it is operating at very low altitudes. For frigates the roll period can be taken to be 8 ÷ 10 sec, FPBs roll more quickly.

Fig. 6 shows in which way ω_{tr} depends on some of the main parameters influencing KIEBITZ dynamics, as the cable length (l_{cable}), the rotor thrust (P_A), and the distance of the platform CG to the tethering point, l_2.

P_A is a function of the relative wind, the available power and the commanded value of the cable tension force, if tethering cable tension is controlled. The relative vertical wind results from the hauldown speed and the vertical gusts.

The moments of inertia do not influence the own natural translatorial frequencies but the rotatorial frequencies as shown in fig. 7. Fig. 7 shows $\omega_{rot} = f$ (l_{cable}, P_A, l_2 and z_S = const). ω_{rot} mainly depends on the rotor thrust P_A and the moments of inertia in the pitch and roll axes. It limits therefore the maximal utilizable P_A because of the cyclic pitch frequency boundary.

Considering these parameters, the equations and data of the automatic controller, the rotor system, the actuators and the environmental factors, it is possible to get optimum configurations of the platform-cable system.

To discuss these problems mathematical digital and hybrid simulation models of the SEA-KIEBITZ have been derived from the models of our operational KIEBITZ. Complete SEA-KIEBITZ operations from ships can be simulated, including the ship and the interaction of ship and helicopter through the tethering cable.

The wave induced motions of ships are statistical and related to those induced by a random sea. In the simulation models they are assumed to be harmonic. They are functions of the significant wave height and the heading angle. For the simulations, the ship has been assumed to be moving at constant heading and speed with respect to the seaway and the prevailing wind and wind direction. The motions of the ship are restricted to heave, pitch and roll.

Physical interaction of the ship and the rotor platform occur through the tether cable and in addition, by the ship's perturbation of the wind velocity profile. The cable tension force is considered in the aircraft model but not the airflow around the ship. The model of the helicopter is a 6-DOF-unsteady model, including a model of the automatic controller and the actuators and a model of the tether cable.

Fig. 8 shows some simulation results of digital simulated flights at low altitudes to get an optimum configuration. For selected heavy ship motions and several low flight altitudes resp. cable lengths, the constant roll attitudes induced by the ship's rolling are plotted over l_2. The left figure is plotted for z_S = const, the right figure for $z_S + l_2$ = const, that means I_x and $I_y = f(l_2)$. Fig. 10 shows the time history of one of these simulated flights.

These results may show that there are ways to get optimum dynamics by discussing the influe of the most inportant dynamical parameters of a tethered helicopter like the SEA-KIEBITZ.

HAUL DOWN PHASE

The dynamical behaviour of the SEA-KIEBITZ and therefore the safe flight envelopes in the phase of hauling down depends on the haul down speed, the ship motions, the relative horizontal and vertical wind and the resulting rotor thrust under consideration of the cable tension force control. It depends too on the reduce of sink rate before onset and the touch down rate.

Fig. 11 shows safe flight- , take-off- and landing-envelopes for the tethered SEA-KIEBITZ in the case of a German FPB (S143). The take-off and mission flight envelopes are satisfactory but for landing on the deck the maximal roll amplitude is limited to 0,2 m. For the landing envelope it was assumed that the sink rate is 2 to 3 m/sec and that the touch down velocity must be very small because of the safe structural loads of the landing gear of the KIEBITZ. The haul down envelope could be extended by decoupling the moving of the tethering point on the deck from the ship's moving, for example by a roll-stabilized landing pad as shown in fig. 2.

The cause for the strong restrictions of the permissible roll attitudes of the ship is the coincidence of the frequency of the ship's rolling and the translatorial own natural frequency of the platform-tether cable-system in flight heights some meters above the deck as discussed before. If the ship rolls too hard the platform is disturbed too much by the oscillating tension forces of the cable which in addition is much more deflected from the vertical than in higher altitudes. Fig. 12 shows a haul down and too big roll attitudes of the SEA-KIEBITZ which are caused by the ship's rolling.

The cable tension depends on the ship motions, the haul down speed and the way of controlling haul down speed.

In some recently completed investigations we have tried to find out the best landing procedure and so to extend the landing envelops, by increasing the haul down velocity and the onset velocity, by diminishing more quickly the sink rate before touch down and by controlling the haul down velocity relatively to the sea level to maintain the cable tension forces at constant values.

The haul down velocity resp. the rate of descent of the SEA-KIEBITZ showed to be limited by the following reasons,

- the influence of the relative horizontal and vertical wind on the system of tether cable and rotor platform
- the flight idle of the turbine which is used in the KIEBITZ and which delivers the compressed air for the torque free blade tip drive (even at flight idle) and the electrical energy for the automatic flight controls, the rotor controls with actuators, the yaw controls and the cable tension control (as said before descent and landing-on by autorotation will not be discussed here)
- the flutter boundaries and the beginning of the vortex ring state.

Fig. 13 shows the sink rate capability of the aircraft as a function of the relative horizontal wind.

Based on these results and the limits of rotorthrust, haul down simulations show that the landing procedure can be improved and the roll boundaries can be extended. As fig. 12 shows the rotor platform SEA-KIEBITZ can utilize higher rates of descent at lower levels of relative horizontal winds.

In general it can be shown that the capabilities of a tethered landing rotor platform to stand higher roll amplitudes of a ship or FPB, can be broadened by a quick haul down at high rotor thrust and a relative high onset velocity. The average rotorthrust should be less at low altitudes above the landing pad because of the coincidence of the translatorial frequency of the tethercable-platform pendulum and the ship's roll frequency but in the contrary it should be high or even increased at this altitude because of the limited touch down speed.

Fig. 14 shows a time history of the variables of motion of a simulated (6DOF) SEA-KIEBITZ quick haul down operation for landing on a FPB. The boat is moving according to sea state 4 at 5 Beaufort headwind. The significant wave period is about 6 sec, the significant wave height is 2,15 m, ship speed is 15 knts and the relative headwind is about 30 kn.

CABLE TENSION CONTROL

It has been shown before how landing dynamics of tethered rotorplatform like the SEA-KIEBITZ can be influenced and improved by the dynamical important parameters and by seeking an optimum landing procedure. But as pointed out before there is still another way of improving landing.

If the haul down speed is constant relatively to the sea level the disturbances of the platform induced by the cable tension can be minimized. There are quite good results if a shipside cable tension control can be realized.

A selected and commanded tension of the tether cable is maintained at a constant value during ship motion and under landing tension by comparing the actual to the selected tension. The resulting error signal is utilized to drive a hydrostatic transmission which maintains the selected tension within narrow limits by turning a winch drum.

The cable tension causes noticeable centering characteristics of the landing helicopter.

CONCLUSIONS

The landing platform motions of SEA-KIEBITZ capable ships in moderately high seas have a very strong effect on the safe landing capability of tethered rotor supported platforms.

Optimum dynamics during the landing procedure can be realized by an optimum configuration, by a high haul down and touch dwon speed and by controlling the cable velocity and tension.

The rotor stop and start limits under consideration of the airflow around the ship have not been discussed here but they are as important as the landing envelope and may too restrict the operational freedom of the ship.

But only trials on a moving landing platform and later on actual sea trials could validate the calculated operational limits.

NOTATION

a	amplitude	m
f	frequency of moving ship	Hz
FPB	Fast Patrol Boat	
I_x, I_y	moments of inertia about aircraft body axes	mkp sec²
l_{AR}	distance rotor-tethering point	m
l_2	distance CG-tethering point	m
l_{seil}, l_{cable}	length of tethering cable	m
M	torque moment of winch drum	mkp
P	Force	kp
P_{AZ}	*cable tension*	kp
P_A	rotor thrust	kp
R_B	Radius of cable drum	m
t	time	sec
z_S	distance of rotor to CG of the helicopter	m
ϕ, θ	Euler angles in roll and pitch	degr.
ω	frequency	1/sec

Subscripts

g	geodetic
A	tethering point
S	CG of aircraft
rot	rotatorial
tr	translatorial

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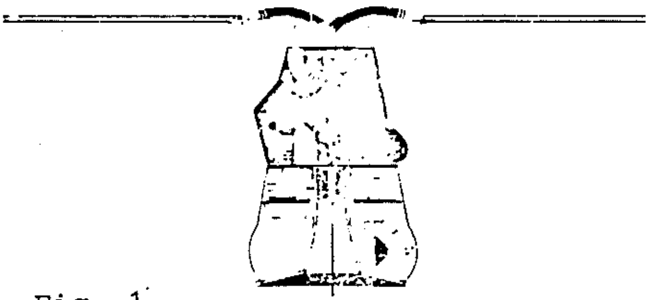


Fig. 1

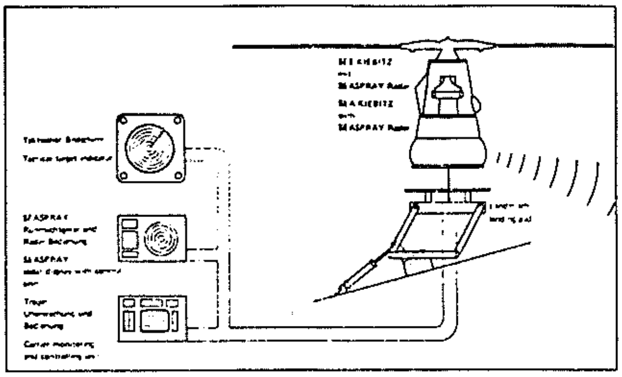


Fig. 2

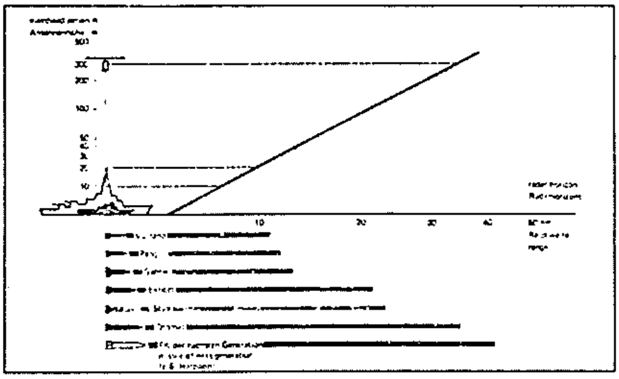
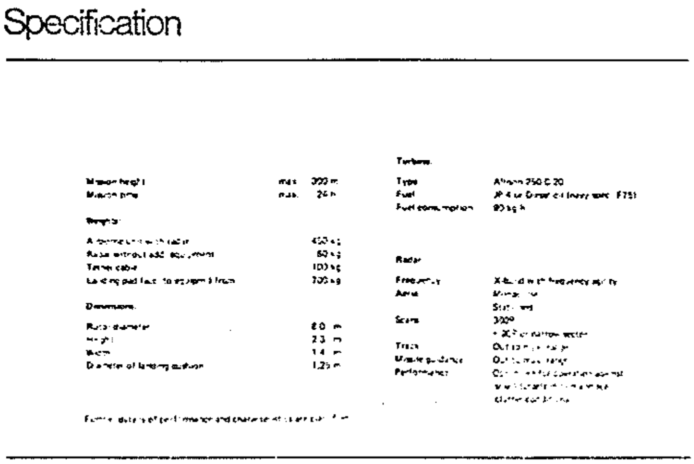


Fig. 3



Specification

Mission height	max.	300 m		
Mission time	max.	24 h		
Weights:				
[illegible]		450 kg		
[illegible]		60 kg		
Tether cable		100 kg		
[illegible]		700 kg		
Dimensions:				
Rotor diameter		6.0 m		
Height		2.3 m		
Width		1.4 m		
Diameter of landing cushion		1.25 m		

Turbine:

Type	Allison 250 C 20
Fuel	[illegible]
Fuel consumption	90 kg/h

Radar

Frequency	[illegible]
[illegible]	[illegible]
	[illegible]
Scan	360°
	[illegible]
Track	[illegible]
[illegible]	[illegible]
Performance	[illegible]

[illegible]

Fig. 4

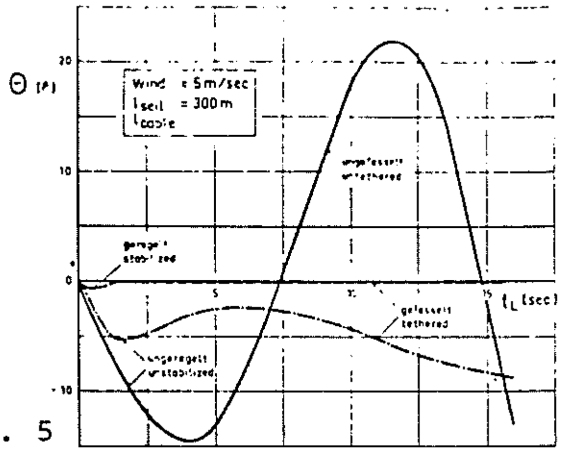


Fig. 5

SEA-KIEBITZ – FESSELSEILEINFLUSS INFLUENCE OF CABLE

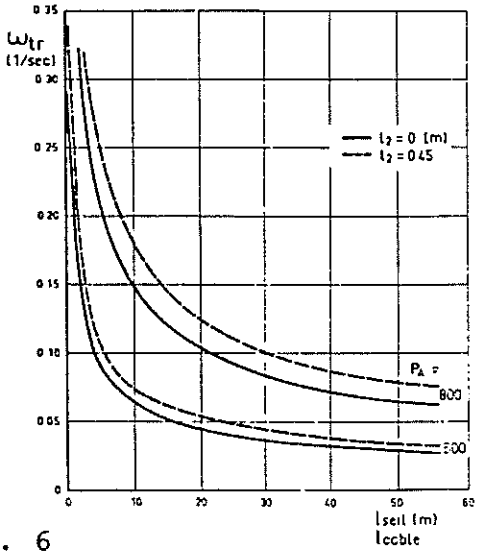


Fig. 6

TRANSLATORIAL OWN NATURAL FREQUENCY
TRANSLATORISCHE EIGENFREQUENZ

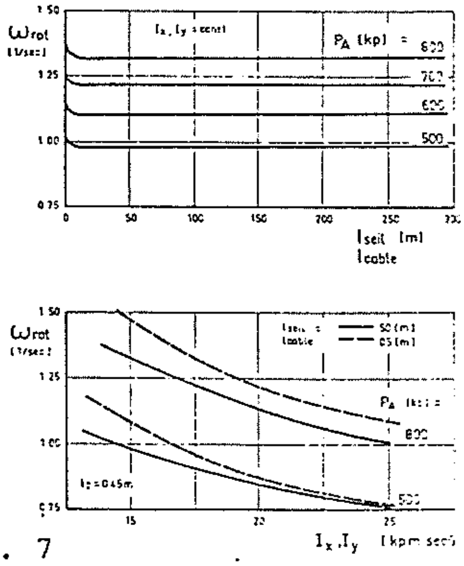


Fig. 7

ROTATORIAL OWN NATURAL FREQUENCY
ROTATORISCHE EIGENFREQUENZ

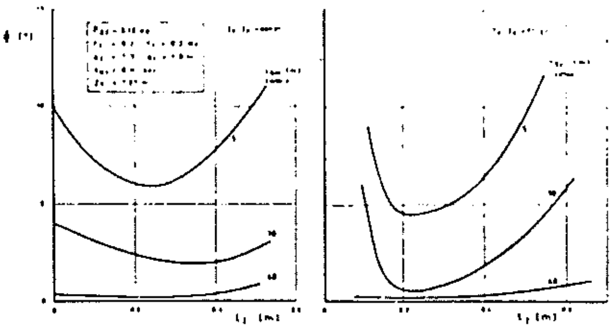


Fig. 8

OPTIMAL DISTANCE CG-TETHERING POINT
OPTIMALABSTAND SCHWERP.-FESSELPUNKT (l_2)

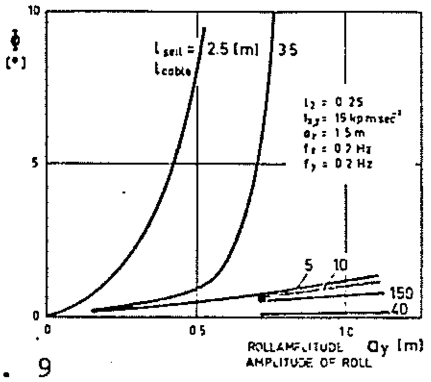


Fig. 9

MAXIMAL ATTITUDES AS A FUNCTION OF CABLE LENGTH
AND ROLL AMPLITUDES OF THE SHIP
BEWEGUNGSVERHALTEN HÖHENABHÄNGIG

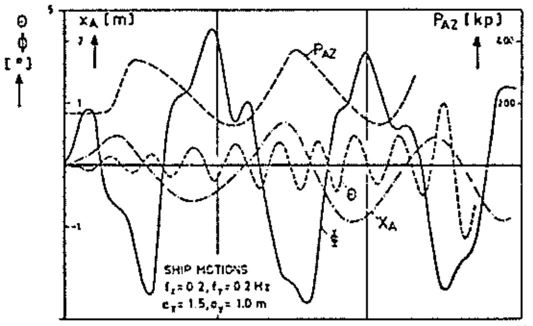


Fig. 10

KIEBITZ MOTIONS 5m ABOVE DECK
FLUGDYNAMIK IN 5m HÖHE, l_2 = 0.22

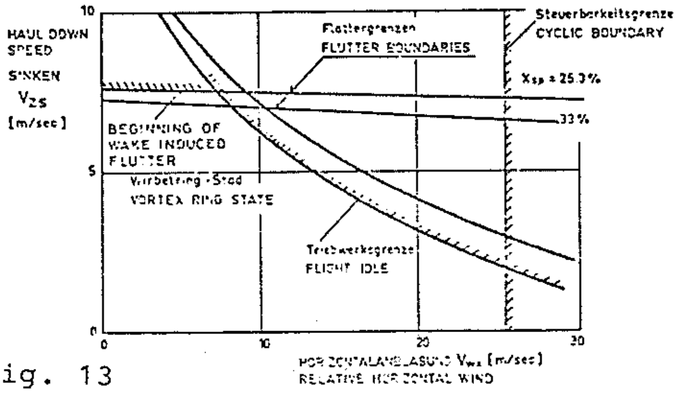


Fig. 13

BOUNDARIES OF HAUL DOWN SPEED
ERLAUBTE SINKGESCHWINDIGKEITEN

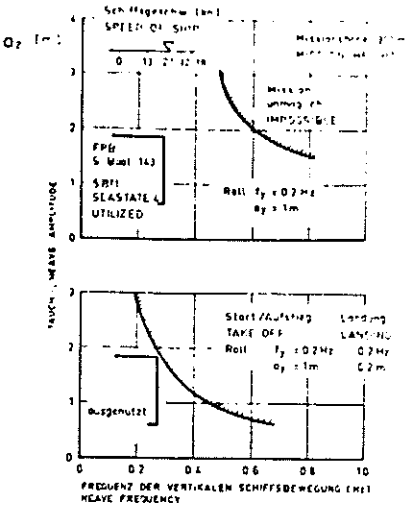


Fig. 11

OPERATIONAL ENVELOPES
EINSATZGRENZEN

Hybridsimulation
Digitalsimulation

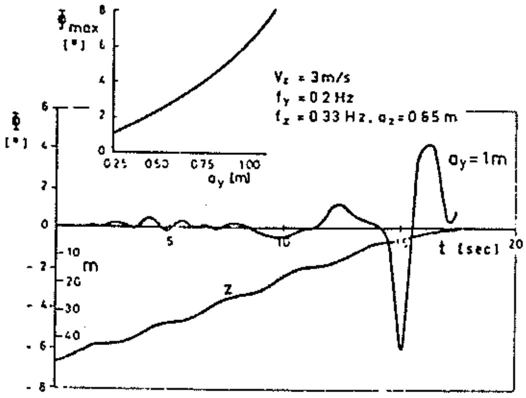


Fig. 12

LAGEWINKELDYNAMIK BEIM LANDEN
ROLL ATTITUDE AT LANDING

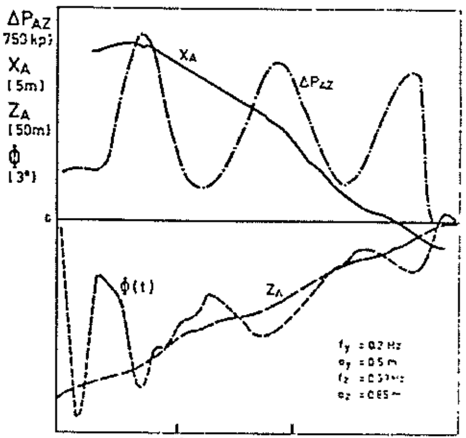


Fig. 14

QUICK HAUL DOWN
SCHNELLES EINZIEHEN
(V_z = 5m/sec, V_{wind} = 15 m/sec)