SECOND EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 12

DYNAMICS OF A SMALL HELICOPTER WITH A HIGH CAPACITY RESCUE HOIST

H. Weiß
J. Stoppel

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

September 20 - 22, 1976

Bückeburg, Federal Republic of Germany

Deutsche Gesellschaft für Luft- und Raumfahrt e.V.

Postfach 510654, D-5000 Köln, Germany

DYNAMICS OF A SMALL HELICOPTER WITH A HIGH CAPACITY RESCUE HOIST

by

H. Weiß
J. Stoppel

Messerschmitt-Bölkow-Blohm GmbH
Postfach 801140
8000 München 80, Germany

SUMMARY

The importance of rescue missions for helicopters has grown significantly in the past years. The BO 105 with its high rotor moment capacity meets the requirements for a lateral swingable hoist without restrictions for the controlability. Only the hingeless rotor, like the rotor system of the BO 105, enables such a small helicopter to operate rescue missions under extreme conditions.

But one problem remains to be solved, that of the coupling between oscillation of the hoist load and the in-plane dynamics of the main rotor.

The BO 105 is able to operate with such a hoist in a restricted operation range - load limit and cable length limit - without the use of additional means. The application of an isolator enables a theoretically unlimited operation range in load and cable length.

Theoretical investigations and extensive flight tests have shown that there is no danger of self-excited oscillations at all.

1. NOTATIONS

A	[m]	Distance between center of gravity and center of rotation of the fuselage
C_L	[Ns/mm]	Damping constant of cable
C_ϕ	[Ns/mm]	Damping constant of fuselage
D_α	[°]	Control input lateral
F_H	[N]	Force at cable hook
H	[m]	Distance between center of gravity of fuselage and rotor plane
K_I	[N/mm]	Spring constant of isolator
K_L	[N/mm]	Spring constant of cable load
K_ϕ	[N/mm]	Spring constant of fuselage
L	[m]	Cable length
M_L	[kg]	Load of hoist
M_ζ	[Nm]	Chordwise bending moment
M_{β_H}	[Nm]	Bending moment of hoist boom
M_B	[kg]	Reduced mass of rotor blade
M_{RED}	[kg]	Reduced mass of fuselage
N	[-]	Number of rotor blades
V_{G_Y}	[mm/s]	Lateral speed at top of transmission
y	[m]	Displacement of rotor hub
z	[m]	Absolut displacement of cable load
γ_L	[%]	Damping ratio of cable
γ_ζ	[%]	Damping ratio of chordwise bending
γ_ϕ	[%]	Damping ratio of fuselage
$\bar{\delta}$	[-]	Normalized damping ratio
ϕ	[°]	Roll angle of fuselage
$\dot{\phi}$	[°/sec]	Fuselage rotational speed

Ω	[Hz]	Rotor frequency
ω_L	[Hz]	Natural frequency of cable load
ω_ζ	[Hz]	Chordwise natural frequency
ω_ϕ	[Hz]	Natural frequency in roll of fuselage
$\omega_{1,2}$	[Hz]	Coupled frequencies of the fuselage
ω_3	[Hz]	Coupled chordwise frequency of blade in fixed system
$\bar{\omega}$	[-]	Normalized frequency ratio

2. INTRODUCTION

The ability of the helicopter to meet the requirements for rescue missions in inaccessible areas is one of its most important features. In general, there are several conditions which can detract from this capability in small helicopters:

The cable load limit
the cable length limit and
the method of getting the injured into the aircraft.

The BO 105 with its hingeless rotor system and its high rotor moment capacity fulfills the requirements for extreme conditions by using a rescue hoist with a swingable boom of about 2 meters of excentricity of the center of rotor. Injured persons can be pulled up to the cabin door with sufficient clearance to the skid. After swinging the boom of the hoist forward it is not hard to pull the injured inside the helicopter.

The limit load for the winch is 270 kg and the maximal length of the cable is 30 meters. The load - an injured person with an assistant, both perhaps in a rescue basket - and the cable make up a dynamic system with a wide range of mass and stiffness parameters.

This undetermined dynamic system is primarily coupled to the rotor in-plane dynamics by its very large lateral distance from the center of rotation. The investigation of these inherent problems and their solutions are discussed here with emphasis on the air resonance.

3. THE PROBLEM OF AIR RESONANCE

The vibrations which are critical in respect to air and ground resonance are determined by the interaction of mass forces due to the in-plane displacement of the center of gravity of all blades and of mass forces due to the displacement of the mass of fuselage. An essential coupling parameter between these movements of blades and fuselage is the relation of the kinetic energy of the lagging blades and the kinetic energy of the inertia of helicopter. The greater the kinetic part of the blades the greater is the danger of increasing oscillations. The vibrations, however, can only increase to critical values, if the dissipation energies of blades and fuselage are lower than the energies available for self-excited vibrations. In this respect the hingeless rotor of the helicopter BO 105 has great advantages. Though the air and ground resonance is first of all a mechanical problem, the aerodynamic forces determine significantly the real behaviour of the rotor and the aerodynamic forces are after all decisive for the damping forces.

Flight tests of the helicopter BO 105 have shown the high damping qualities of the hingeless rotor. The typical damping values are several times higher than those of a rotor with articulated rotor blades. According to these tests and also to theoretical investigations the helicopter BO 105 is stable even if the resonant rotor speed is nearest the operating range in the air resonance state. Any critical natural modes which may appear are sufficiently damped.

4. ANALYTICAL MODEL

All masses and their displacements which are important for the theoretical investigation of the resonance problem of the helicopter with excentric load in hovering are shown in Fig. 3. The equations of motion of the system can be developed from the energy balance. The kinetic energies are those of the fuselage owing to the roll mode, those of the cable load due to the roll mode and the vertical load displacement and those of center of gravity of all blades owing to the roll mode and the displacement out of the center of the hub.

The potential energies results from a stiffness in roll, which is first of all an aerodynamic value, the stiffness of the cable and the chordwise bending stiffness of the blades.

The dissipated energies are derived from the structural damping of the fuselage, the cable, and the blades and from the important aerodynamic damping forces.

To get the connection between the displacement of the center of gravity of all blades and the in-plane movement of the four blades, a substitution is made by using the coordinates of the sum of the displacement components of the single blades in the fixed system [1].

5. FLIGHT TESTS OF HELICOPTER WITH LATERAL HOIST

For the helicopter with lateral hoist the cable loads will change the frequencies of the system in such a way, that for certain cable lengths an aircraft body frequency involving horizontal hub motion is equal or close to the difference between the rotor speed and the in-plane natural frequency. Fig. 4 shows an example of this.

In the first case (L = 10 m) the resonant condition does not occur. The helicopter with excentric load in hovering flight is relatively quiet at the beginning of the test. Only after a short lateral control input in an impulse-like form by the pilot the helicopter will execute a motion in roll - here the speed in roll of the fuselage is measured - which however will disappear after a short time.

The reaction of the cable load has been found by the measurement of the force working on the hook. Also the oscillations of the load are damped out rapidly.

The chordwise bending motion of the blade, important for the air resonance likewise, decreases relatively fast. The harmonic analysis of the chordwise bending moment shortly after the control input shows the dominating rotor speed frequency part and a very low in-plane frequency part.

In the second case of Fig. 4 the resonant condition has been fulfilled by altering the cable length (L = 20 m). You will see typical amplitude limited vibrations which will occur without being influenced by the pilot. During all the measurements a continual oscillation of the cable load can be seen, which, on the other hand, will influence the motion in roll of the fuselage and the chordwise bending motion of the blades. Now a significant part of the natural in-plane frequency is analysed in the chordwise bending moment besides the usual rotor speed frequency part.

From many measurements of flights with different cable loads and lengths limits can be determined, where oscillations occur with a significant part of natural frequencies (Fig. 5). Above and below these limits the part of the natural frequencies is very low. Limits can be fixed for safe operations in the rescue of persons and in the transportation of loads. The difference is due to the damping effect of persons on the cable, which will shift the limit up.

Tests with an additional isolator between the end of the cable and the load showed a shifting of the limit according to the stiffness of the isolator (Fig. 6). From the measurements followed a shifting of the limit in the direction of smaller loads and shorter cable lengths, that means lower energy of the load and therefore lower damping forces are required.

6. THEORETICAL INVESTIGATIONS

Together with the flight tests theoretical investigations on the dynamic behaviour of the helicopter with lateral hoist were performed.

The frequency diagram of the helicopter in Fig. 7 shows the essential frequencies of the system decisive for the resonance problem to be examined here. These frequencies are the uncoupled frequencies of the fuselage ω_ϕ and the cable load ω_L, which will change into the coupled frequencies ω_1 and ω_2 and the exciting frequency ω_3 which is almost identical with the uncoupled frequency $\Omega-\omega_\zeta$.

In consequence of the high nonlinearity of the stiffness of the cable (approximately quadratic characteristic) the frequency of the cable load changes with the cable length and the cable load in a large range and in consequence of the coupling the frequency of the fuselage will change, too.

Thus for a certain cable length the condition of the air resonance will occur. Here the risk of increasing oscillations exists, if the damping is unsufficient and the energy, which the rotor provides to the system by way of the in-plane oscillating blades, cannot be compensated.

The curves of the roots in Fig. 8 give an information about the damping behaviour of the system. There are two special points for the helicopter without hoist, one for the roll motion (lower point) and one for the chordwise bending motion (upper point). These points are far enough from the stability limit, which also has been confirmed by tests. From these two points curves of the roots of the helicopter with hoist start. The lower branches are valid for the coupled oscillations of the fuselage and the cable load. The upper branch shows the damping of the critical mode. It can be seen that with increasing cable length the damping behaviour deteriorates rapidly after an initial improvement. If the cable length is further increased, the damping behaviour improves again and approaches the case of the helicopter without a hoist.

In Fig. 9 curves of roots are shown, which are essential for stability, The upper curve is valid for the helicopter with a hoist but without an isolator. With an isolator, that means with the insertion of an additional spring between the end of the cable and the load, the form of the curves of the roots do not change in spite of decreasing stiffness. The region of instability is only shifted to smaller cable lengths.

Starting with a certain softness of the isolator the area of instability will not be touched any more. When the stiffness will further decrease, the curve of the roots is contracted almost to a point, which is identical with the root of the helicopter without hoist.

7. CORRELATION BETWEEN ANALYSIS AND FLIGHT TEST RESULTS

The essential behaviour of the helicopter with a hoist is shown in Fig. 10. In absence of an isolator there exists the possibility of a resonance of the exciting frequency with a coupled natural aircraft body frequency in consequence of the great nonlinearity of the stiffness of the cable. This resonance cannot be avoided in the whole operation range of the cable length. The respective damping curve shows the possible instability of the system. If an isolator is used, the resonance will shift to smaller cable lengths. In case of sufficiently small stiffness of the isolator the frequencies of the cable load and the air-frame are practically uncoupled. Both frequencies now are beneath the exciting frequency in the whole area. The damping exponent remains practically constant.

From these findings a stability diagramm (Fig. 11) can be developed. There is a tube-like area of instability which remains constant for large values of the stiffness of the isolator. Only with relatively small stiffnesses a shifting towards smaller cable length becomes visible.

But the important fact is that below a certain stiffness of the isolator the complete operation area is free of resonance. This diagram is valid for a certain cable load. For other cable loads the limits of stability change only insignificantly. The absence of resonance in the area of lower stiffness of the isolator is not touched.

These theoretical investigations have been completely confirmed by flight tests of the helicopter with lateral hoist and an isolator with a small stiffness ($K_I = 22$ N/mm).

The following measurements in Fig. 12 have been executed for flight tests with cable lengths from 0 to 30 m. The action of the pilot is measured by the lateral control input. The reaction of the fuselage is shown by the speed in roll at the top of the transmission. In all cases the fuselage returns rapidly to its original state. The bending moment of the hoist boom indicates the reaction of the cable load. No oscillations of the cable load is visible besides the reaction to the impulse. There is almost no reaction of the blades as well, which can be seen in the measured chordwise bending moment.

8. CONCLUSION

In spite of the relatively low gross weight (2300 kg) the BO 105 with its hingeless rotor system is able to operate a rescue hoist of 2 m excentricity and a cable load of 270 kg. By the use of a simple isolator - consisting of very soft spring without an additional damping device - there are theoretically no limitations in cable length. The existing limitation in cable length (30 m) are imposed by practical considerations. Theoretical investigations and extensive flight tests have proved that there is no danger of self-excited oscillations in the whole operation range.

9. REFERENCES

[1] Coleman, Feingold
Theorie of Self-excited Mechanical Oscillation of Helicopters with Hinged Blades,
NACA tn 3844, 1957

[2] Lyntwin, R.T., Miao, W., Woitsch, W.
Airborne and Ground Resonance of Hingeless Rotors,
Preprint No. 414, 26th Annual National Forum of the American Helicopter Society,
Washington, D.C., June 1970

[3] Woitsch, W., Weiß, H.
Dynamic Behaviour of a Hingeless Fibreglass Rotor,
Research, Design, and Operations Meeting,
Atlanta, Georgia, February 1969

[4] Huber, H., Miao, W.
Rotor Aeroelastic Coupled with Helicopter Body Motion,
Presented at the Meeting on Rotorcraft Dynamics NASA-Ames Research Center,
Moffett Field, California, February 1974

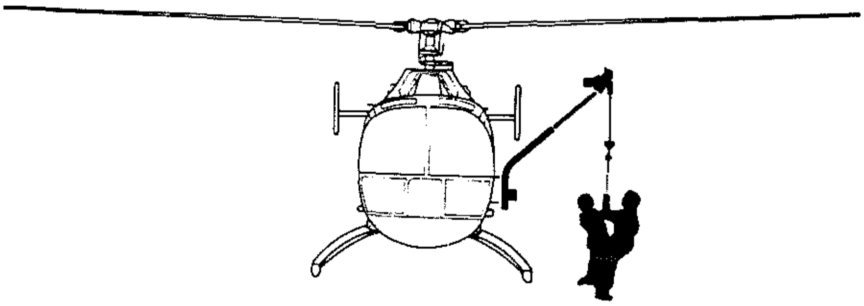

Figure 1: BO 105 with lateral hoist (schematic)

Figure 2: BO 105 - Rescue mission

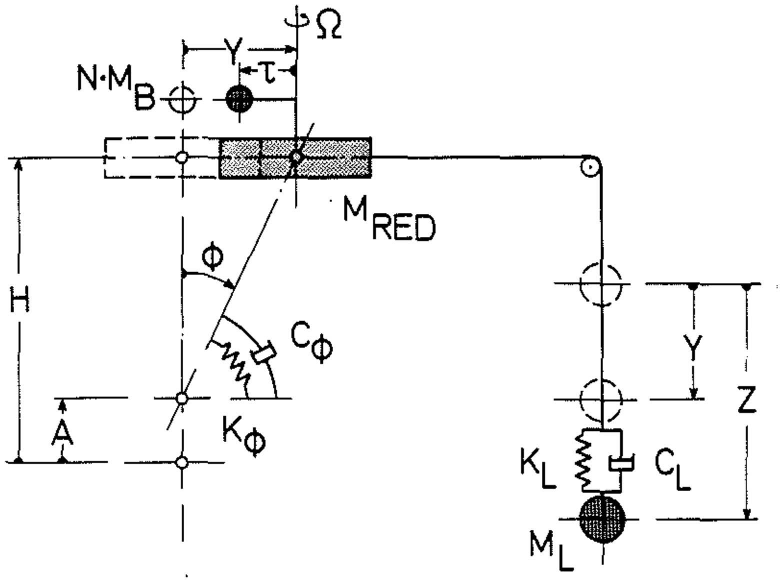

Figure 3: Analytical model of helicopter with lateral hoist

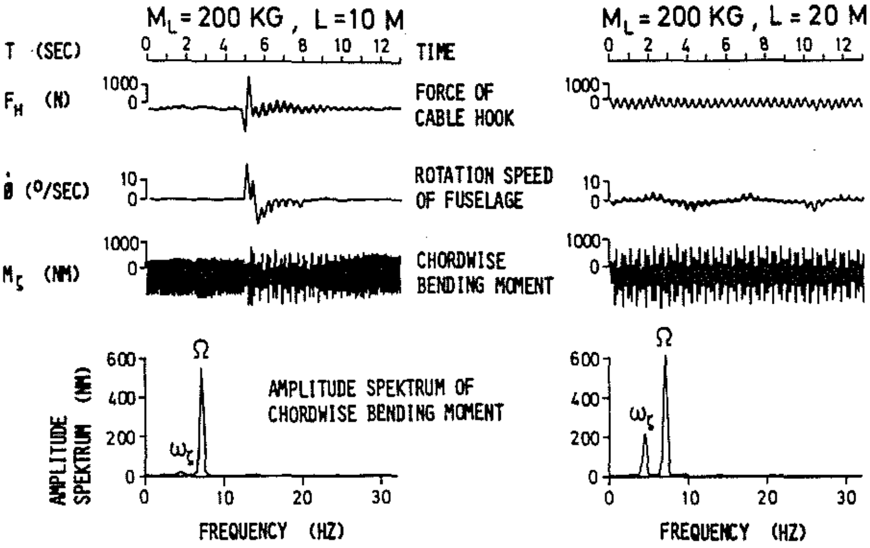

Figure 4: Dynamic behaviour of helicopter with hingeless rotor and with lateral hoist

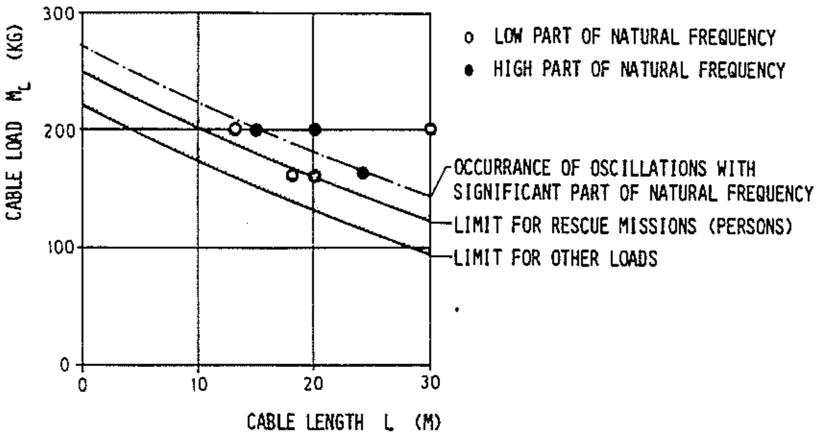

Figure 5: Operation limit for helicopter with lateral hoist and without isolator

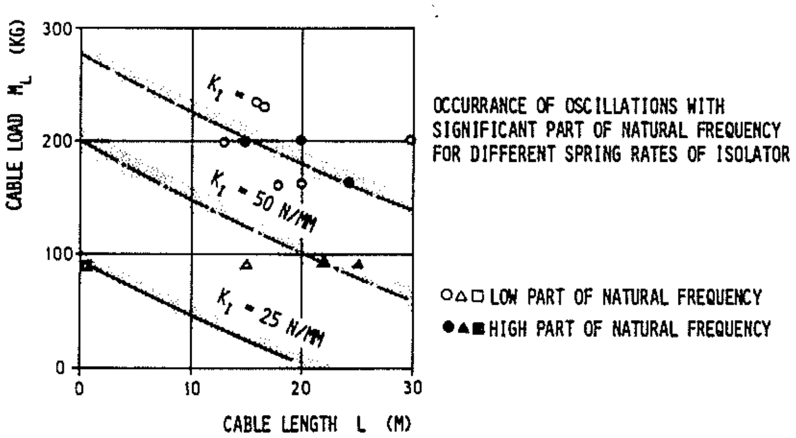

Figure 6: Influence of an isolator on operation area for helicopter with hoist

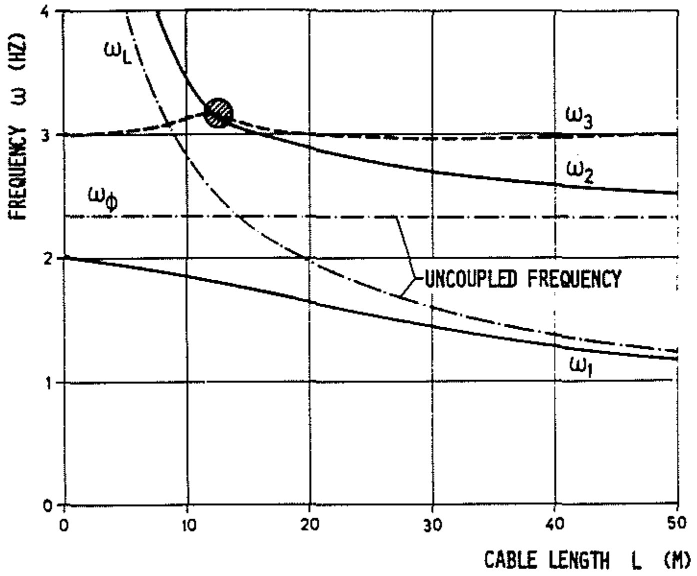

Figure 7: Frequency diagram of helicopter with lateral hoist

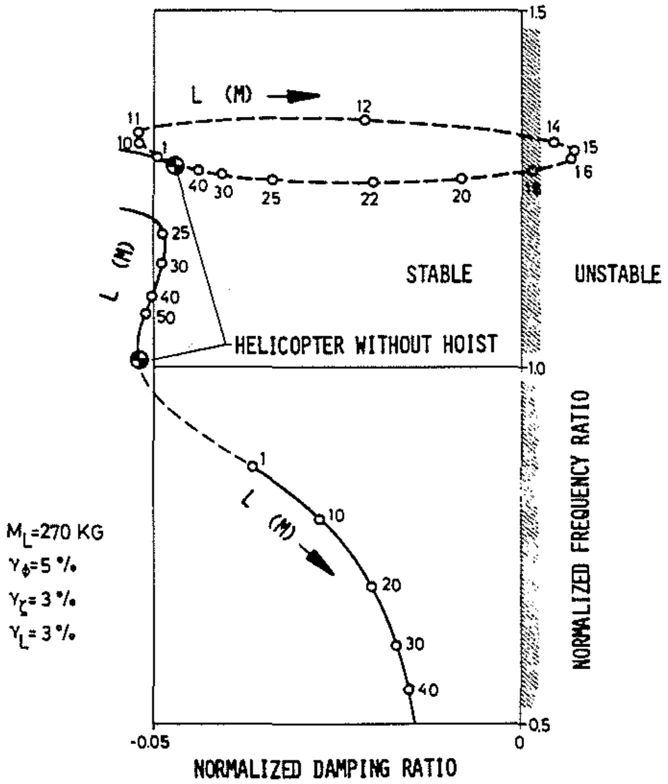

Figure 8: Root locus of helicopter with hoist

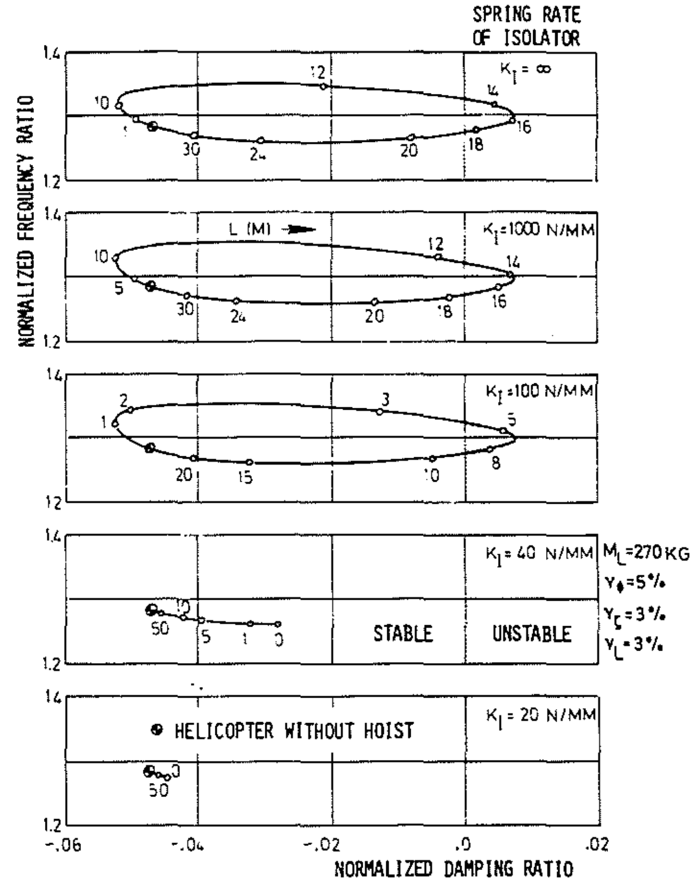

Figure 9: Effect of isolator on dynamic stability

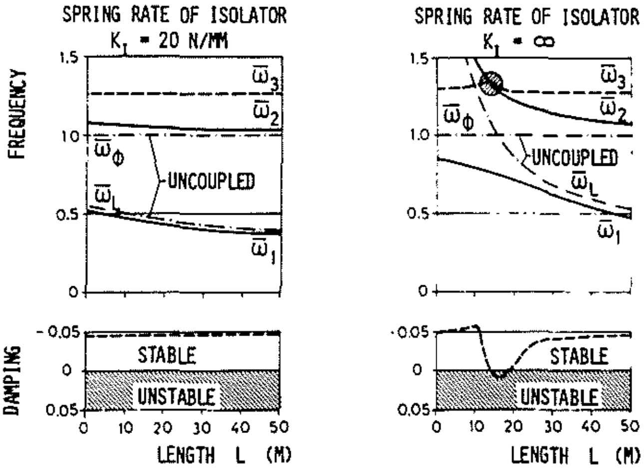

Figure 10: Effect of isolator on dynamic stability

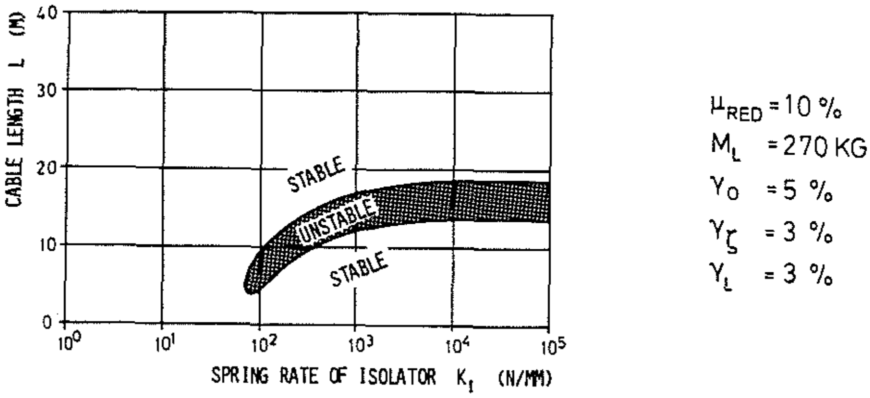

Figure 11: Stability diagram of helicopter with lateral hoist and isolator

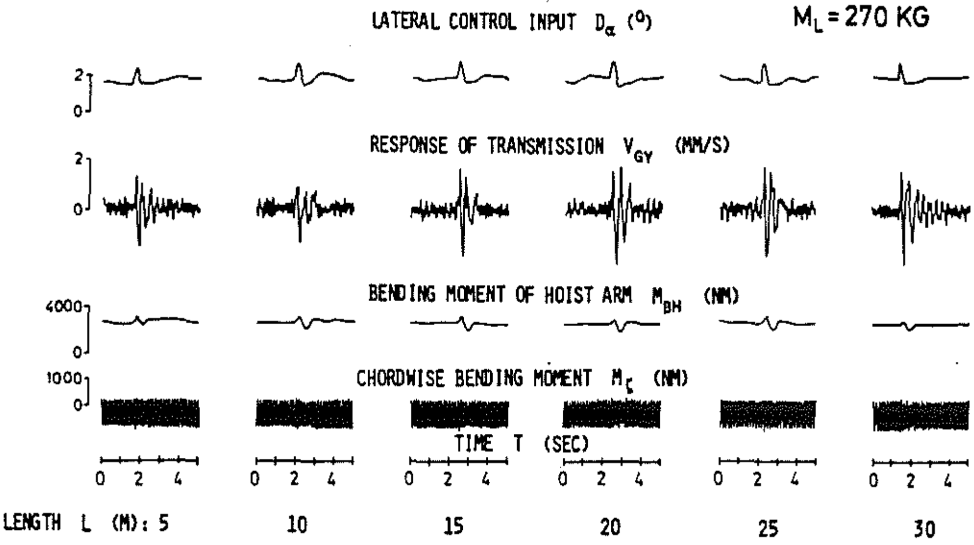

Figure 12: Test results of helicopter with lateral hoist and isolator