FLIGHT TESTING OF PIONEER BRIDGES AS HELICOPTER SLUNG LOADS USING A CH-53G

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Abstract. Mobile pioneer bridges of different types were transported as helicopter slung loads in a test campaign in order to identify safe flight envelopes, handling qualities as well as practical handling instructions. The German Federal Armed Forces intend to standardize and to establish procedures of the external load transportation of pioneer bridges. Tests were carried out by means of a 20to CH-53G medium lift transport helicopter in close cooperation of the Wehrtechnische Dienststelle 61 (WTD 61, the German Armed Forces Technical and Airworthiness Center for Aircraft and Aeronautical Equipment), the Wehrtechnische Dienststelle 51 (WTD 51, German Armed Forces Technical Center for Pioneer and Troop Equipment) and the DLR (German Aerospace Center), where preparatory activities have been conducted by simulation in advance [1]. The paper will discuss test preparations and results.

Notations

c_{dp}	[-]	drag coefficient	P	[W]	rotor power
D	[N]	drag force	S_i	[m^2]	projection screen
g	[m/s^2]	gravity constant	T	[N]	rotor thrust
m	[kg]	mass	V_j	[m/s]	downwash velocity
$\dot{m}$	[kg/s]	mass flow rate	ρ	[kg/m^3]	air density

1. INTRODUCTION

Helicopter slung load operations are essential for manifold missions, such as search and rescue, disaster relief, supply of remote locations, and military support operations, respectively. The German Armed Forces intend to transport fully pre-installed mobile bridges as helicopter external loads. The main specifications of desired aerial transportable lightweight bridges in future include a maximum weight of 5to/11000lbs and a maximum length of 22m/72ft. The bridges must be performance-ready after positioning and disembarkation. This means in particular that the track systems must be mounted when the bridges are transported leading to load shapes which may be prone to increased aerodynamic activities. Up to now, the bridges are being carried disassembled inside the helicopters cargo bay. Hence, the bridges have to be installed at the construction area, where under certain circumstances neither heavy equipment nor a sufficient number of ground staff will be available.

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The motivation is to enlarge operation capability of ground troops in terms of the immediate availability of pioneer bridges when they are needed, and to gain troop mobility due to the absence of heavy equipment, such as trucks and cranes.

Before the helicopter external transportation of these new load structures is approved, general feasibility and safety for the crew as well as for the overall system helicopter plus slung load must be demonstrated and guaranteed for all phases of the transport mission. The approval is noted in form of a detailed process instruction for both helicopter and ground crew, including envelope limits, for instance. Therefore, flight tests have been conducted in order to gather informations about proper handling procedures as well as flight envelope limits and operational hazards, such as intensive load swinging and vertical bounce phenomena, respectively.

Researches of helicopter external load transportations have been conducted ever since helicopters were used to carry underslung loads. The focus lied on either analysing the load’s impact on the helicopter’s handling qualities or on investigating means of load stabilization. In recent past, investigations on handling qualities have been conducted by [2] and [3], for instance. Extensive analyses concerning simulation and stabilization of slung loads have been accomplished by [4] [5] [6] .

For the flight tests, three prototype bridges of different specifications were available (q.v. table 1). The first bridge featured a weight of 4.3to/9500lb and a length of 21m/70ft. Its specifications were similar to those of the desired bridge mentioned above. However, this bridge (framework structure) could not be transported with its track system installed due to construction and safety reasons. The second bridge provided a weight of only 2.5to/5500lbs and a length of only 12m/40ft. This bridge could not be transported with its track system either (framework structure). A third bridge featured 2.3to/5100lbs and a length of 9.6m/31ft. This bridge was entirely made of carbon fibre reinforced plastic (CRP) and provided a fully closed surface. Hence, each bridge provided an extract of the desired specifications mentioned previously. However, neither featured them all. Therefore, the characteristics of the important specifications had to be evaluated separately.

The tests were planned and carried out by the German Armed Forces Technical and Airworthiness Center for Aircraft and Aeronautical Equipment (WTD 61) as well as for Pioneer and Troop Equipment (WTD 51), and the German Aerospace Center (DLR). Each of the three prototype bridges was capable to carry vehicles of up to 12 metric tons weight (MLC 12).

	Bridge 1	**Bridge 2**	**Bridge 3**
overall weight	4.3 to / 9500 lbs	2.5 to / 5500 lbs	2.3 to / 5100 lbs
length/width/height	21.3 / 3.8 / 2.2 m	12.0 / 4.8 / 1.3 m	9.6 / 3.8 / 0.8 m
	69.8 / 12.5 / 7.2 ft	39.4 / 15.7 / 4.3 ft	31.5 / 12.5 / 2.6 ft
suspension harness	4-point	4-point	4-point
raw material and	steel	aluminium	CRP
type of structure	framework	framework	fully closed structure
with or w/o track system	open bottom surface	open bottom surface	closed bottom surface

Table 1: Specifications of the prototype pioneer bridges

The first bridge was instrumented with sensors. Tensile forces in the four straps of the suspension harness and high frequency oscillations of the load body structure at five different locations were recorded by means of strain gages and accelerometers, respectively (q.v. figure 1). The measuring equipment consisted of the sensors, a laptop computer and a battery for self-sustaining electric power supply. In order to simplify the flight approval procedure, the equipment was installed directly onto the bridge without a direct link to the helicopter. Thus, no power supply through the helicopter's systems was needed. The natural frequencies of the first bridge with the suspension harness attached were derived from dynamic ground tests conducted by the manufacturer prior to the flight tests.

The CH-53G is operated by two pilots (test and safety pilot) as well as a flight test engineer and a load master. The aircraft provides conventional mechanical helicopter controls that are augmented by two parallel and independent hydraulic servo systems. Collective control is cross fed to the lateral cyclic as well as the tail rotor controls in order to compensate for roll and yaw moments produced by collective pitch changes. The electronic Automatic Flight Control System (AFCS) includes command augmentation of longitudinal cyclic control, rate damping about all axes, attitude and heading stabilization, and turn coordination at indicated airspeeds above 60 knots (q.v. table 2). Helicopter related parameters were recorded on tape at 120 Hz and transmitted simultaneously to a telemetry station for online monitoring. Air data were measured by means of a nose boom.

For qualitative analyses, questionnaires for the pilots, the flight test engineer, and the onboard technician have been prepared. Feasibility of the load transportation was evaluated, and applying conditions as well as general operational characteristics were recorded.

weights		**performance**	
max. gross weight	19,050 kg (42,000 lbs)	engines	2 x T-64-GE-7
max. external load	7,255 kg (16,000 lbs)	cont. power	2 x 2,409 kW
		max. speed at SL	315 km/h (170 kts)
number of load hooks	1	cruise speed at SL	278 km/h (150 kts)
main rotor		**tail rotor**	
number of blades	6	number of blades	4
type	articulated	diameter	4.88 m (16 ft)
diameter	22.02 m (72 ft)	rated frequency	82.8 rad/s
rated frequency	19.4 rad/s		

Table 2: Specifications of the WTD-61 Sikorsky CH-53G testbed [2]

2. GROUND AND FLIGHT TEST PREPARATION

The transport mission was subdivided into eight consecutive phases:

- 1st preparation of the bridges
- 2nd installation of the suspension harness
- 3rd lifting the bridges by the helicopter to hover condition (out of ground effect: OGE)
- 4th transition from hover (OGE) to forward flight
- 5th manoeuvre flights (forward flight, full circle, and slalom)
- 6th transition from manoeuvre flight to hover (OGE)
- 7th positioning and disembarkation
- 8th post processing

The phases were assigned to either ground handling or aerial transportation. The phases 1, 2, and 8 dealt with the preparation and the post processing of the load on ground. Phases 3 to 7 were related to individual episodes of the aerial transportation. For every phase the application of standard procedures was verified according to the flow chart in figure 2. Standardized procedures of helicopter load transportation apply for every external load mission. They are either objective in terms of documented process instructions, or subjective in terms of procedural methods accomplished intuitively by the pilots. The transportation of pioneer bridges represented a novelty and was therefore challenging. Firstly the dimensions of the bulky bridges exceeded those of conventional load bodies, such as light vehicles and other troop equipment. Secondly, if transported fully pre-installed, aerodynamic effects could occur and influence handling qualities.

The standard procedures for the preparation of helicopter slung loads on ground as well as the aerial transportation are well known and documented, i.e. for light vehicles and similar bulky loads, respectively. The applicability of standard procedures was tested for each test phase concerning operability and safety (q.v. figure 2). Operational limits, work and flight instructions as well as technical comments were documented for each phase. In case of non-applicability, the procedures were modified to meet the requirements that guarantee operability and safety. These modifications were realized by the pilots during the flights. If the modified procedures were still not applicable, new procedures were specified, and flight tests were repeated (q.v. figure 3). Break conditions were installed in case of the ultimately non-applicability of procedures as well as reaching the limit of flight test hours. Break conditions applied when overall safety could not be warranted and the manoeuvres could not be accomplished after two modifications according to the flow chart in figure 3, respectively.

Ground tests applied for the phases 1, 2, and 8. The attention in phases 1 and 8 turned to the ground handling concerning the proper (dis-)assembly of the bridges and the documentation of necessary precautions that must be taken, i.e. selection of solid subsoil and cleaning up the hover zone for obvious safety reasons, respectively. The installation of the suspension harness in phase 2 was tested with the aid of a crane (q.v. figure 4). The attachment points of the straps at the bridge structure were chosen concerning the optimal relation between minimum spread angle and tilt-stability of the load. The suspension harness was built up of several straps being towed together. This assembly was approved and certified, and was tested for practical realization and applicability.

Flight tests applied for the phases 3 to 7. A flight test programme was defined as the execution of six test trials for each bridge (q.v. table 3). The trials consisted of the five related phases and were separated by speed and type of manoeuvre (q.v. phase 5 in table 3).

flight test programme per bridge					
1st test trial	**2nd test trial**	**3rd test trial**	**4th test trial**	**5th test trial**	**6th test trial**
phase 3: lifting hover	***phase 3:*** lifting hover	***phase 3:*** lifting hover	***phase 3:*** lifting hover	***phase 3:*** lifting hover	***phase 3:*** lifting hover
phase 4: accelerating 0-40 KIAS	***phase 4:*** accelerating 0-60 KIAS	***phase 4:*** accelerating 0-40 KIAS	***phase 4:*** accelerating 0-60 KIAS	***phase 4:*** accelerating 0-40 KIAS	***phase 4:*** accelerating 0-60 KIAS
phase 5: forward flight 40 KIAS	***phase 5:*** forward flight 60 KIAS	***phase 5:*** full circle 40 KIAS	***phase 5:*** full circle 60 KIAS	***phase 5:*** slalom 40 KIAS	***phase 5:*** slalom 60 KIAS
phase 6: decelerating 40-0 KIAS	***phase 6:*** decelerating 60-0 KIAS	***phase 6:*** decelerating 40-0 KIAS	***phase 6:*** decelerating 60-0 KIAS	***phase 6:*** decelerating 40-0 KIAS	***phase 6:*** decelerating 60-0 KIAS
phase 7: positioning hover	***phase 7:*** positioning hover	***phase 7:*** positioning hover	***phase 7:*** positioning hover	***phase 7:*** positioning hover	***phase 7:*** positioning hover
landing	landing	landing	landing	landing	landing

Table 3: Flight test programme

For each bridge, three manoeuvres were accomplished; these were straight forward flight, full circle, and slalom.

Because lifting and positioning were accomplished solely at hover condition (0 KIAS), phase 3 and 7 were repeated six times each per bridge. Phase 4 was distinguished between the acceleration from 0 to 40 KIAS and 0 to 60 KIAS, respectively. The same separation applied for the deceleration in phase 6. Hence, both phases were repeated three times at one speed per bridge. Phase 5 was separated by speed and type of manoeuvre. No repetitions were accomplished. Hence, each manoeuvre flight remained unique.

Flight test hours are always limited. The classification of the transport scenario into phases aimed at concentrating on the diverse test episodes. In doing so, the test phases could be analysed individually. A high number of repetitions of the test phases guaranteed validity of the results, although flight test hours were reduced to a minimum.

For each bridge a test programme of 90 minutes duration was specified consisting of six test trials. After each trial the pilot landed shortly beside the load and released the harness in order to attend to the questionnaire. The evaluation of each phase was mainly dedicated to the primary test goals: determining flight envelope limits, and evaluating handling qualities as well as practical handling instructions. For evaluation purposes, rating scales were provided, which were divided into five categories including further explanations (i.e. control activity: aggressive – active – moderate – passive – restrained). In order to simplify the examination of the questionnaires for the helicopter crew, the pre-formulated answers as well as the ratings were to be marked with crosses.

3. FLIGHT TEST RESULTS

In the following the test results of the different phases will be discussed for each bridge type. Applying ambient test conditions are listed up in table 4. The respective configuration of the helicopter slung load systems is shown in figure 5.

	Bridge 1	Bridge 2	Bridge 3
mean QNH	1015 hPA	1023 hPA	1023 hPA
mean wind	070/8 crs/kts	var/2 crs/kts	070/8 crs/kts
temperature	20°C / 68°F	20°C / 68°F	20°C / 68°F
ceiling	overcast	clear	clear

Table 4: Average flight test conditions

3.1 Lifting the Bridges to Hover Condition (OGE)

Bridge 1 The pilots and the technicians evaluated the lifting of the 4.3to bridge as operable without limitations. Problems which arose during the phase execution did not differ from those that appeared with other loads. These problems concentrated in general on anti-clockwise load turning. However, the turning rate of the load body was much higher than for conventional loads. Two reasons were determined for this phenomenon. Firstly, the distance between rotor and slung load accounted for approximately 22 metres (72 ft), which equalled the rotor diameter. The velocity of the rotor downwash maximizes at approximately one times the rotor diameter beneath the rotor, which turns anticlockwise. Secondly the load dimensions were greater than these of conventional load bodies. The bridge features a greater surface that stayed in contact with the downwash as well as longer lever arms. Thus, forces and moments acting at the bridge due to the rotor downwash increased and resulted in greater turning rates. The impact of the load on the helicopter due to swinging and turning was negligible. Control limits were not reached.

The demand of torque in order to lift the bridge load (95% torque needed) was higher than it has been determined prior to flight testing (85% torque calculated). The rotor power applying for hover condition can be calculated utilizing the momentum theory [7] (q.v. figure 7). From the assumption that the flow is quasi-steady, and by the principle of conservation of mass, the mass flow rate, $\dot{m}$, must be constant within the boundaries of rotor wake:

$$\dot{m} = \iint_{1} \rho \vec{V} \cdot d\vec{S} = \iint_{2} \rho \vec{V} \cdot d\vec{S} = \rho \cdot S_1 \cdot V_1 = \rho \cdot S_2 \cdot V_2 \quad \left[{}^{kg}\!/\!{}_{s} \right] \tag{1}$$

The rotor thrust, T, is equal and opposite to the overall take off weight which included both, the helicopter’s take off weight as well as the weight of the external load. The momentum theory leads to a relation between the rotor thrust and the induced velocity at the rotor disk:

$$T = \iint_{2} \rho \cdot \left(\vec{V} \cdot d\vec{S} \right) \cdot \vec{V} = \dot{m} \cdot \left(V_2 - V_0 \right) \quad [N] \tag{2}$$

The overall take off weight accounted for 17844kg/39340lbs which led to a theoretical demand of rotor power of 2.427MW which corresponded to 85% torque. The calculated velocity in the rotor disk plane accounted for 13.67 m/s (V_1) which led to V_2 = 27.34 m/s. The formula for the rotor power is given with:

$$P = \frac{1}{2} \cdot \dot{m} \cdot \left(V_2 - V_0\right)^2 \quad [W] \tag{3}$$

However, 95% torque was needed in order to lift the bridge, which in turn corresponded to 2.712MW rotor power and an actual V_1 of 14.19 m/s. The difference accounted for 0.285MW which complied with a difference of 1370kg/3020lbs in take off weight. This increase in torque which corresponded to an increase in thrust which in turn was related to an increase in the overall weight was explained by additional drag forces acting at the bridge due to the rotor downwash.

In order to determine the drag force acting at the bridge due to the rotor downwash, a linear approximation considering the orthographic flow against an idealized flat plate (c_{dp} = 1.23) can be accomplished according to equation 4. The flow velocity equates the downwash velocity V_2 = 28.38 m/s at level 2 (q.v. figure 7), since the load was located at a distance of one rotor diameter (22m/72ft) beneath the rotor disk plane.

$$D_{idealized} = \frac{\rho}{2} \cdot V_2^2 \cdot S_{projection} \cdot c_{dp} \quad [N] \tag{4}$$

The idealized drag force is related to the additional weight derived above as follows:

$$D_{idealized} \triangleq \Delta m \cdot g = 1360 kg \cdot g = 13341.6 \; [N] \tag{5}$$

Using equation 4, this relation leads to an effective drag surface of

$$S_{(Bridge\ 1)} = 22m \left[m^2\right] \; / \; 236.8 \left[sq\ ft\right]$$

Therefore, it can be summarized, that the rotor downwash acted at about 27% of the closed projection screen of bridge 1 that was built as framework structure:

$$S_{(Bridge\ 1\ closed)} = 21.3m \cdot 3.8m = 80.9 \left[m^2\right] / \; 872.5 \left[sq\ ft\right] \tag{6}$$

Improving the lifting scenario according to the flow charts (figures 2 and 3) the standard suspension harness was elongated by 3 metres (9 ft) in order to disarrange the bridge out of the area of maximum downwash-velocity. This modification increased the handling qualities due to the deceleration of the load turning, and reduced the demand of torque significantly.

Bridge 2 The lifting of the 2.5to bridge was evaluated as operable without limits. Standard procedures applied. The load influence on the helicopter was negligible. Control limits were not reached and the demand of torque stayed within the amount derived in advanced. The load body was much smaller compared to bridge 1, and hence, provided less contact surface. The turning of the load was moderately according to conventional slung loads.

Bridge 3 The lifting of the third prototype bridge providing a weight of 2.3to was evaluated as operable without limits using standard procedures. The overall take off weight accounted for 15644kg/34489lbs which led to a theoretical demand of rotor power of 1.976MW which corresponded to 71% torque. The actual torque demand during the flight test was increased by about 9% to 80% overall. This increase in torque and therefore in rotor power resulted once again from additional drag forces acting at the bridge due to the rotor downwash. They were related to an additional weight of 1301kg/2868lbs according to the formulas 1 to 3. Using equations 4 and 5, and the related downwash velocity V_2 = 25.75m/s the effective drag surface of bridge 2 accounted for 25.56m^2. Therefore, it can be summarized, that the rotor downwash acted at about 70% of the closed projection screen of bridge 2 providing a closed CRP-structure of 36.5m^2/393 sq ft.

The turning of the load was moderately according to conventional slung loads.

3.2 Transition from Hover (OGE) to Forward Flight

Bridge 1 In a first phase run the pilot accelerated from hover condition to 40 KIAS forward flight, later on to 60 KIAS. During the acceleration the rapid turning bridge stabilised at about 20 KIAS across flight direction. The acceleration to 40 KIAS was evaluated as operable without limits using standard procedures. The influence of the load on the dynamics of the helicopter was negligible during the acceleration as well as after reaching the final speed. The pilot workload was not increased compared to conventional loads. Hence, the flight envelope was not limited, and handling qualities were not derogated.

The manoeuvre ‘accelerating to 60 KIAS’ was evaluated as operable in general. However, the trial was interrupted at 55 KIAS due to heavy alternating motions in helicopter pitch. At this point the influence of the load on the helicopter was considerably noticeable and was evaluated as strong. The pilot workload was increased and led to heavy control activities. Due to the air flow the bridge was deflected backwards and produced not only high drag forces that needed to be compensated by the helicopter, but also alternating moments around the helicopter’s centre of gravity due to alternating load swing angles (q.v. figure 6).

The straps of the suspension harness started to vibrate with increasing forward speed. In the range of low speeds (up to 40 KIAS) the oscillations stayed moderate and the dynamic influence of the vibration on the load as well as on the helicopter was negligible. This phenomenon was explained by the Karman Vortex Street and is called ‘Sling Leg Web Flapping’ in literature [8]. However, at speeds above 50 KIAS the vibrations started to influence the load by transmitting the oscillations to the attachment points of the load. The pilots and the technicians evaluated this phenomenon as a potential threat to the overall system due to a potential loss of controllability. Furthermore, the vibrations could violate the mechanical limits of the bridge. Therefore, going faster than 55 KIAS forward flight was not recommended and defined as flight envelope limit.

The helicopter, the suspension harness, and the external load are equivalent to a dynamic system of two masses connected by a spring. A disturbance to this system can excite a vertical oscillation at the natural frequencies of the overall system – fuselage, straps, and load - which under normal circumstances would damp rapidly. However, the presence of the pilot and his thrust lever control can add another element to the system which can lead to a divergent oscillation which is called vertical bounce phenomenon [9]. The suspension frequency of the load is significant. Slings which lead to natural frequencies of the overall system which are close to or resonant with the rotor one-per-revolution frequency are the only ones which diverge. This phenomenon means a threat to both, the helicopter and the load, respectively.

The natural frequencies of the suspended bridge 1 were evaluated by the manufacturer by means of crane tests using the same suspension harness as for the flight tests. The respective frequencies are listed up in table 5. However, neither data for the natural frequencies of the fuselage nor the subsequent natural frequencies of the overall system – fuselage, straps, and load - were available. With respect to the results shown in figure 8, it must be recognized, that

mode	1st bending mode	1st torsion mode	1st bending-torsion mode	2nd bending mode	2nd bending-torsion mode	3rd bending mode
natural frequencies [Hz]	16.7	18.4	22.4	29.9	35.5	42.4
rotor harmonics [Hz]	19.4	38.8	58.2	77.6	97	

Table 5: Natural frequencies of bridge 1 and rotor harmonics

the natural frequencies of the overall system would vary slightly compared to those of the suspended bridge 1 (blue dashed dotted lines) due to the fuselage influence.

Figure 8 shows the frequency spectrum in z-axes at the measuring points 1 to 5 (q.v. figure 1) in hover flight. The measuring period accounted for 140 seconds, thereof 80 seconds in hover condition after lifting from ground. After this period, the measuring equipment failed.

A significant frequency appeared in the range of 25Hz at the measuring points 2 and 4, which were located symmetrically (q.v. figure 1). This frequency is close to the first bending-torsion mode of the bridge (q.v. table 5). However, because the sensors at the measuring points 1, 3, and 5 did not record any amplitude in this frequency range, the peak in measurements could be related more likely to the second bending mode at about 30Hz. The frequency was located between the first and second rotor-harmonics. Considering all multiples, no indication was given that divergent oscillations occurred due to the rotor harmonics which would be related to the vertical bounce phenomenon. Therefore, overall system's natural frequencies were not changed by the straps, so they would correspond to the rotor harmonics. The frequency spectra in the z-axes of all five sensors constitute a rather stochastic distribution. Thus, divergent oscillations did not occur. The overall system was damped satisfactorily.

Bridge 2 The acceleration of the second bridge to 40 and 60 KIAS, respectively, was accomplished by using standard procedures. The turning rate of the bridge decreased constantly. The bridge remained stable across flight direction at about 30 KIAS. The influence of the load on the helicopter dynamics was negligible. The pilot workload was not increased compared to conventional slung loads. The straps were stimulated to light vibrations, which did neither affect the load nor the helicopter. At 60 KIAS the load was deflected backwards at a stationary level of about 45 degrees which means a maximum deflection in common practice. Thus, going faster than 60 KIAS forward flight was not recommended (flight envelope limit).

Bridge 3 When accelerating to 40 KIAS, the CRP-bridge oscillated by ±20 degrees about the yaw axis at a stationary deflection of about 30 degrees backwards. The phase was accomplished without limitations by using standard procedures. However, the alternating turning implied the danger of a total turning (360 degrees). In this case, stability of the load could get lost.

When accelerating to 60 KIAS, the load oscillated by ±5 degrees about the yaw axis at a stationary deflection of about 40 degrees. The heavy alternating motion in helicopter pitch recurred which was already known from the first bridge (q.v. figure 6). Hence, the pilots evaluated the phase 'accelerating to 60 KIAS' as operable with limitations. Going faster than 60 KIAS forward flight was not recommended (flight envelope limit).

3.3 Manoeuvre Flight

3.3.1 Forward Flight

Bridge 1 The forward flight at 40 KIAS was accomplished without limitations by using standard procedures. The load remained stable across flight direction, and its impact on the helicopter was negligible. Helicopter pitch accounted for about -5 degrees which represented a rather unusual flight condition compared to regular external load transportations. Normally, helicopter pitch would have been about zero to low positive degrees. The considerable negative pitch and the increase in torque were both indicators for high drag forces acting on the bridge which needed to be compensated by helicopter thrust.

The phase was interrupted at 55 KIAS forward flight again, when the alternating pitch motion in helicopter pitch recurred. The helicopter pitch accounted for about -10 degrees. The straps of the suspension harness vibrated heavily. Hence, the flight envelope was limited to 55 KIAS (q.v. figure 9).

Bridge 2 The phase was accomplished at both speeds without an increase in pilot workload or any limiting phenomena. The load remained stable and the impact on the helicopter dynamics was negligible. Helicopter pitch accounted for about -5 degrees (figure 10 and 11). However, the angle of deflection of the slung load was about 45 degrees backwards which was evaluated as operational maximum load deflection before. Thus, the flight envelope limit was set to 60 KIAS.

Bridge 3 The load oscillated about the yaw axis by ±20 degrees at 40 KIAS with a stationary deflection of about 30 degrees backwards. This did not influence the helicopter dynamics. At 60 KIAS forward flight, the alternating pitch motion in helicopter pitch recurred (q.v. figure 6). Like before this phenomenon represented an envelope limiting factor. However, the load remained stable in yaw. Helicopter pitch accounted for about -5 degrees (figure 12). The flight envelope was therefore limited to 60 KIAS.

3.3.2 Full Circle

The purpose of the full circle manoeuvre was to evaluate the load's turn coordination at constant load factors.

Bridge 1 Due to the problems occurring at 60 KIAS, which had been identified in foregoing test trials, the full circle manoeuvre was accomplished at 40 and 50 KIAS. The circle was flown at bank angles in the range of -15 to -20 degrees. The test phase could be accomplished without limitations at moderate control activities. The influence of the load on the helicopter dynamics was negligible. The load's lateral axis was turning according the circle motion and remained parallel to the helicopter's centre line. The load behaved vibration-neutral.

Bridge 2/3 For both bridges the manoeuvre could be accomplished satisfactorily at 40 and 60 KIAS without limitations. The circle was flown with about -20 degrees bank angle. The load turned parallel to the helicopter's longitudinal axis.

3.3.3 Slalom

The purpose of the slalom manoeuvre was to evaluate the load's turn coordination and its directional stability at load-cycle changes. Furthermore, the impact of the load on the helicopter dynamics under varying load factors was determined.

Bridge 1/2 The slalom manoeuvres were accomplished at bank angles in the range of -20 to +20 degrees for both bridges at 40 and 50 KIAS. It was shown that a regular slalom manoeuvre was not reproducible. Due to the load's weights and the high load factors the pilot did not have enough control power to command slalom manoeuvres of arbitrarily executed agility. Instead of that, the overall systems helicopter plus slung load executed pendulum motions at frequencies close to the theoretically derived pendulum frequency (~0.125Hz for a pendulum with about 16m/52.5ft length) according to:

$$f = \left(2\pi \cdot \sqrt{\frac{L_{pendulum}}{g}} \right)^{-1} \quad [Hz] \tag{7}$$

The loads remained stable at all times and their influence on the helicopter was considerably noticeable. Both bridges featured a similar body structure which was an open framework structure. Neither aerodynamic instabilities nor lifting effects due to the body surface occurred. The dynamic behaviour of both loads under load-cycle changes was therefore comparable to conventional drag bodies. The lateral axes of the loads remained aligned with the helicopter's centre line. Due to the lack of manoeuvrability, the overall system was characterized as inactive and sluggish.

Bridge 3 The body structure of the third bridge was different compared to the bridges 1 and 2. The surface was completely closed, similar to a flat plate structure. It was therefore assumed that this load would develop not only drag forces but also lift forces when attacked by varying flow directions. The presence of unsteady aerodynamics in general was expected. Causes and effects of aerodynamic instabilities at bluff bodies have been intensively analysed by the NASA Ames Research Center, i.e. in [10] and [11]. In terms of safety and controllability, the straps of the suspension harness must always be charged with the load's weight. Thus, external loads must never be lifted due to aerodynamic effects. This would limit the flight envelope to a manoeuvre speed that prevents the bridge from being lifted.

When the slalom manoeuvre was started at 20 KIAS with alternating bank angles of ±20 degrees, the load behaved different. The load did not execute pendulum motions according to the mechanical pendulum frequency (7) applying for conventional drag bodies. Instead, the bridge accomplished diverse motions that were neither predictable nor controllable. The load's amplitude was increasing constantly during oscillations. A reason for that was seen in unsteady aerodynamics acting at the bridge. At 20 KIAS the load swung sidewards as well as forth and backwards. By swinging forth, the bridge developed a positive angle of attack with respect to the flow. The resulting lifting force exceeded the load's weight, which in turn, was lifted up and fell back into the suspension harness in an uncontrollable manner (q.v. image series in figure 13). This bounce effect was critical for multiple reasons. First of all, the stress limits of the straps could be exceeded due to very high load factors, which could lead to cable ruptures, and hence, the loss of the load. Secondly, the load body was not controllable during the period of its free flight. Thus, in the moment when the straps were discharged the flight conditions were different to those when the straps were charged again, because the load changed its position during the free fall. The change in the general flight conditions could lead to serious irritations of the pilot. Third of all, when the load bounced back into the strap, the helicopter was stressed temporarily with a multiple of the regular load factor. This dynamic impact on the flight conditions can affect safety seriously. Furthermore, structural damages of the fuselage could occur.

The manoeuvre could only be tried to be accomplished at a speed of 20 KIAS, when the load swinging already began. This behaviour was characterized as extremely threatening to the helicopter and marks a limiting factor for the transport operation. It must be guaranteed that a load bounce and an uncontrolled ascending of closed bridge structures never occur. Therefore, it was determined, that speeds over 20 KIAS exceed the flight envelope limit.

3.4 Transition from Manoeuvre Flight to Hover (OGE)

Pilots and technicians evaluated the decelerating of all three bridges as operable without limits using standard procedures. When approaching to hover condition, the loads started to turn anti-clockwise. The influences of the loads on the helicopter were evaluated as negligible.

3.5 Positioning and Disembarkation

The positioning of the bridges was assisted by ground personnel who adjusted the bridges according to ground marks which represented the positioning areas. The areas were of same size than the respective bridges. Each bridge provided a rest surface at both sides of 0.5m/1.6ft times the bridge width. The specifications defined a minimum overlay of 0.3m/1ft times the bridge width between rest and soil in order to guarantee stability. Thus, the translational position accuracy may have varied about ±0.2m/0.6ft, which was determined as the desired precision. After positioning and disembarkation, the offset between the actual load position and the desired position (ground marks) could be measured.

Two ropes were attached to the edges of each bridge as means for the turning coordination. Beside the position accuracy the duration from approaching and positioning to finally disembarking the load was evaluated.

Bridge 1 When the helicopter was approaching the bridge was directional stable. The bridge began to turn anti-clockwise during the transition from slow forward flight to hover condition (OGE). The 4.3to load was firstly positioned roughly above the marks and subsequently descended. The translational fine-positioning was accomplished by the pilot. The turning coordination was accomplished by the ground staffs. However, they were hardly able to control the turning of the bridge by means of the ropes.

The main problem in positioning the bridge was that the pilot could not see the load. Hence, translational corrections were advised the pilot by the ground staffs and the load master, respectively. In doing so, time delays occurred between the appearance of load displacements and the related corrective control inputs. The positioning was therefore hindered. The longer the positioning manoeuvre took, the more increased the pilot work load was. In turn the loss of concentration led to worse positioning results. Further corrections were necessary. Eventually, the manoeuvre was not accomplished satisfactorily. The final load displacement with respect to the ground marks did not meet the manoeuvre requirements.

In order to enhance the positioning performance, the transport procedure was modified according to the flow chart in figure 3, and flight tests were repeated. The standard suspension harness was elongated by 3 metres (9 ft). This reduced the turning of the bridge in hover significantly. Due to the increase in length, the pendulum frequency was reduced. Hence, the dynamic reaction of the load due to control inputs developed much slower, which led to a decrease of pilot workload. Furthermore, the turning coordination could be accomplished satisfactorily by the ground personnel due to a reduction in the turning rate of the bridge. The positioning manoeuvre was conducted more precisely and faster compared to the shorter suspension harness. However, the desired precision could not be achieved due to the problems mentioned above.

Bridge 2 As expected the bridge turned anti-clockwise when the helicopter approached and decelerated to hover condition. Again, the ground personnel stopped the turning of the bridge by means of the ropes and adjusted the load according to the ground marks. The pilot was able to eventually position the load more precisely compared to the first bridge. A reason for that was evaluated in the lower weight, leading to firstly a negligible dynamic influence on the helicopter, and secondly an easier handling for the ground personnel. The pilot workload was evaluated as lower compared to the flight test with bridge 1. The difficulties of time delays mentioned above between load displacement (cause) and corrective control inputs (action) remained. However, the manoeuvre was accomplished in a minimum of time, although the desired precision could not be achieved.

Bridge 3 Similar to bridge 2 the third bridge was translational positioned. The aerodynamic activity of the load due to the rotor downwash complicated the turning control by the ground personnel due to hindered handling. The problems which occurred due to time delays between reporting the load displacement and controlling in a corrective manner were even amplified compared the other loads. Because the load master was not able to see through the fully closed CRP-bridge in contrast to the framework structures, a loss of orientation and a lack of survey of the positioning area occurred. Thus, reporting the load displacement was mostly tardy and imprecisely. The desired position accuracy was not achieved.

4. CONCLUSIONS

The flight tests gave insight into operation conditions. Although no bridge with the finally desired specifications was available, important results concerning flight envelope limits and potential operational hazards were determined using three different prototype bridges. These bridges provided partially representative specifications.

The most important influencing parameters identified were the weight of the bridges, their dimensions, and the aerodynamic activity due to the method of construction which led to either an open or closed surface. Hence, this activity caused firstly an increase in the demand of rotor power due to the rotor downwash acting at the effective drag surface of the respective bridges. Secondly, during manoeuvre flights, the aerodynamic activity may lead to additional drag forces due to the incoming flow and the ability to produce lift forces at the bridge.

Therefore, three critical flight phases were identified; these were hovering, manoeuvre flight with load-cycle changes, and load positioning.

When hovering with load structures providing great effective drag surfaces like bridge 1 and 3, respectively, the demand of rotor power compared to the theoretical derived demand considering solely the load's weight was increased significantly. It was determined that the actual demand of rotor power was increased by about 10% when lifting bridge 1 which provided an open bottom surface due to its framework structure. The effective drag surface that was affected by the rotor downwash accounted for 27% of the closed projection screen of bridge 1 considering its dimensions in length and width. The additional weight due to rotor downwash accounted for 1370kg/3020lbs. When hovering with bridge 3, which provided a fully closed bottom surface due to its CRP-construction, the increase in rotor power accounted for about 9%. However, due to the smaller dimensions the percentage of the affected closed projection screen was much higher and accounted for about 70%. The additional weight due to rotor downwash accounted for 1301kg/2868lbs. If the dimensions of bridge 3 were greater in terms of meeting the desired specifications but also affected by 70%, it can be determined according to the formulas 1 to 5, that the additional weight due to rotor downwash would account for about 3700kg/8100lbs. Considering the increase in weight of a CRP-bridge that meets the desired specification - 22m/72ft in length – the helicopter's external load capacity would be exceeded.

The aerodynamic activities of slung loads may decrease manoeuvrability and agility as well, and may even endanger the overall system due to uncontrollable motions and dynamics. Due to the incoming flow in forward flight, unsteady aerodynamics may apply at the load and lead to fast alternating reaction forces resulting in unpredictable motions. In a worst case, the load can even produce lift forces due to a positive angle of attack with respect to the flow, and may finally be lifted up as happened in flight tests. In this case, the straps of the suspension harness are discharged, leading firstly to an immediate change in helicopter flight conditions. Secondly, the load covers a distance without any control. Consecutively, the location where the load falls back into the straps will be different compared to that when it was lifted up. Thus, the helicopter is being stressed with a very high load factor acting in an unpredictable direction. This phenomenon is critical for the maximum loading capacity of the straps, the helicopter fuselage that may be damaged due to overload, and, most importantly, the helicopter dynamics that are being disturbed vastly.

High weights of slung loads usually limit the helicopter's agility. Manoeuvrability concerning control authority is decreased considerably. With respect of the load's weight it has been determined that load-cycle changes could only be accomplished meeting the mechanical conditions in terms of executing pendulum motions. The overall system could not be controlled arbitrarily.

The most critical flight phase was therefore identified as manoeuvre flight with load-cycle changes. However, in terms of meeting mission requirements, the load positioning was critical as well. The positioning could not be accomplished satisfactorily. The pilot could not see the load. Hence, control advisories had to be given by ground personnel. This induced time delays in the corrective control inputs. The longer the positioning took, the more the workload of the pilot and the ground staffs increased, leading to the need of further positioning corrections.

The vertical bounce phenomenon did not occur. The overall system was damped satisfactorily, and no divergent oscillations were stimulated.

5. SOLUTIONS AND FUTURE WORK

Two main areas of interest have been identified: firstly, positioning must be simplified, and secondly, pendulum oscillations that may endanger the system must be avoided under any circumstances.

A rather simple as well as practicable solution to improve positioning results was given with the elongation of the suspension harness. The bridges were removed out of the area of maximum rotor-downwash influence, and the pendulum frequency was decreased. Hence, not only the dynamic reactions of the bridges in terms of turning and oscillating were diluted, but also the additional demand of rotor power due to the rotor downwash acting at the bridge's drag surfaces was decreased. Furthermore, the visibility of the pilots was improved because of the higher distance between the pilot-station to ground. Due to this measure, the workload of the pilots and the ground personnel was reduced. The positioning results were determined as considerably better accomplishable compared to the short standard suspension harness.

In terms of guaranteeing a direct information link to the pilot regarding a potential positioning offset, position cues are needed. They may be provided by systems, such as mirrors that are installed beneath the pilot station as well as precise GPS-data, for instance.

Further investigations have to be conducted regarding potential means of damping load oscillations without decreasing in speed and positioning loads precisely. Controllability during flight with respect to pendulum oscillations can be reduced by slowing down significantly. The danger of unpredictable load motions due to the aerodynamic activity is minimized. However, this might conflict with mission requirements.

Furthermore, analyses regarding the potential threat of the vertical bounce phenomenon must be conducted in all test phases. The vibration characteristic must be analysed in terms of changing the natural frequencies of the overall system – fuselage, straps, and load – by elongating the straps and changing the load masses, respectively. The specifications of the bridges differ from regular external load bodies. They are prone to high frequency oscillations more easily due to their body structure, and provide natural frequencies that are close to the rotor harmonics.

In terms of the significance and validity of test results, repetitions are always supposed to be as high as possible. Furthermore influencing factors on the desired outputs must be known. These requirements are often contrary to the availability of flight test hours. Against this background, the applicability of the DOE-method (design of experiment) must be reviewed for future flight tests. DOE represents a method to determine influencing factors and their interdependencies on the desired output values. At the same time, the number of test repetitions is minimized. For the current flight tests, variations in flight speeds and changes in the lengths of the straps are best suited as influencing factors.

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FIGURES

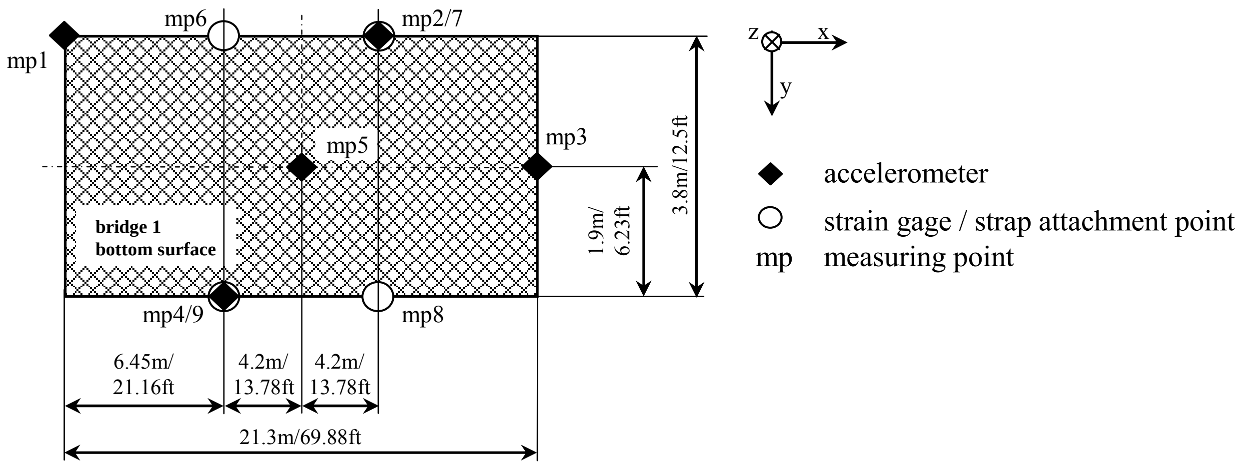

Figure 1: Sketch of measuring points at bridge 1

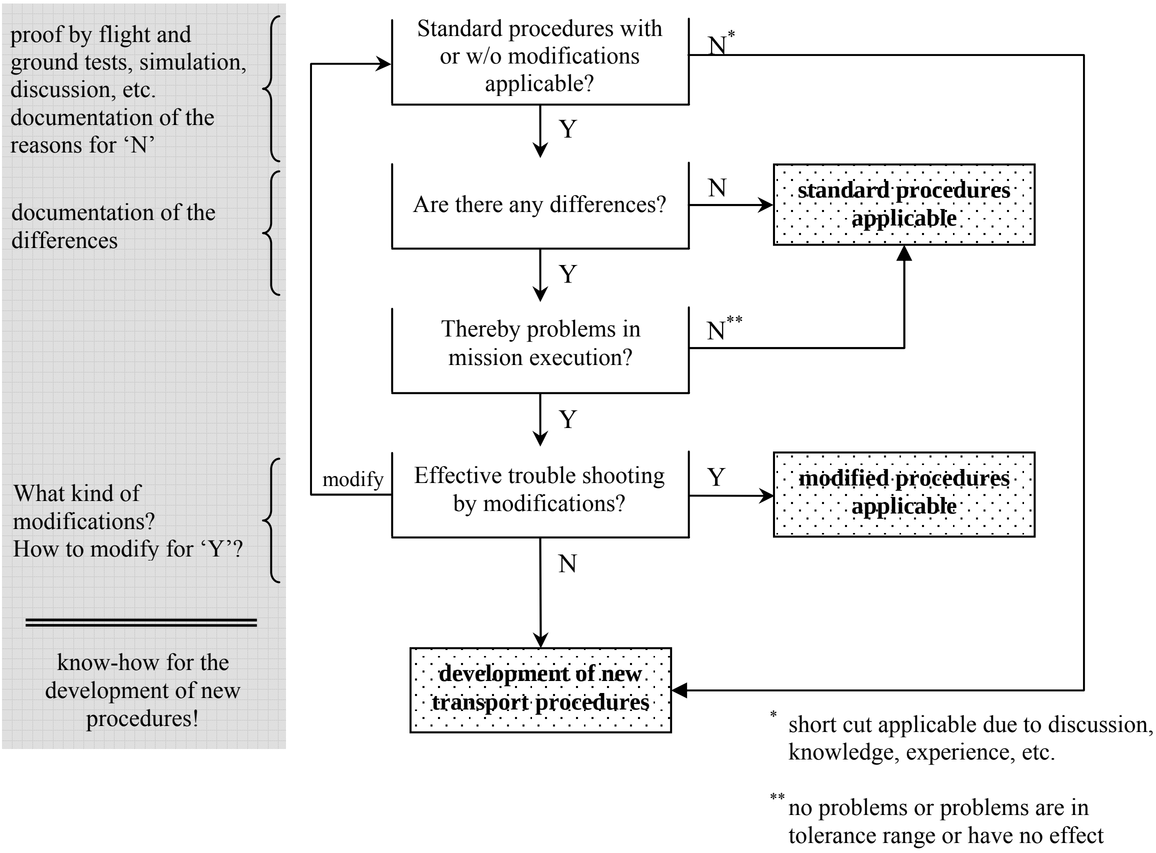

Figure 2: Flow chart - verifying standard procedures

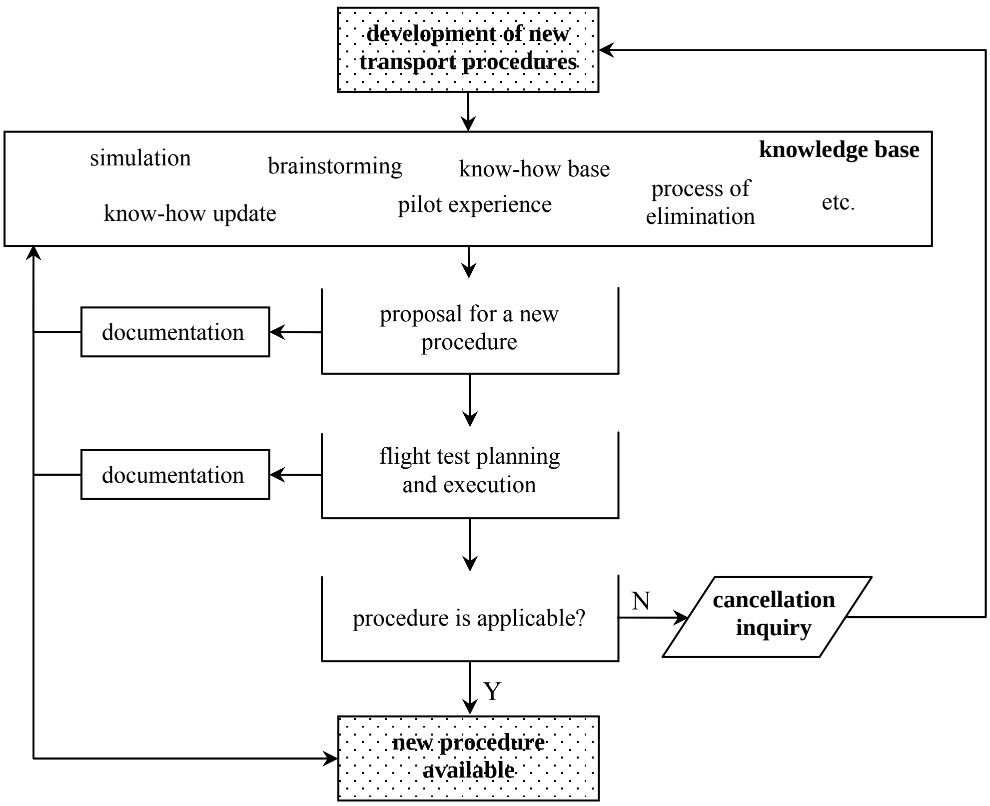

Figure 3: Flow chart – developing new procedures

Figure 4: Ground tests at bridge 1

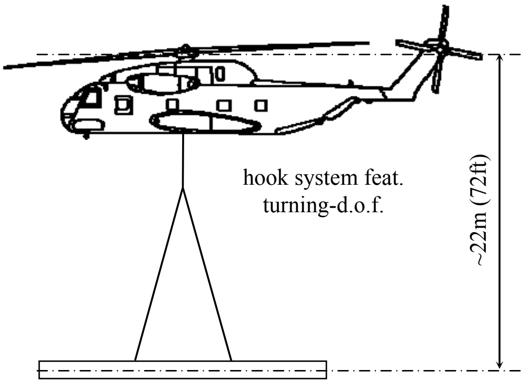

Figure 5: Helicopter slung load configuration

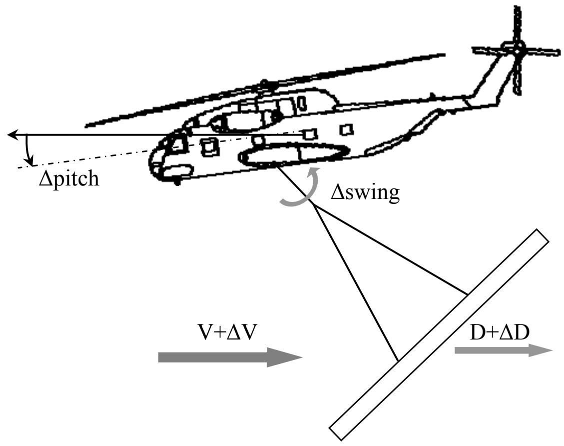

Figure 6: Load influence

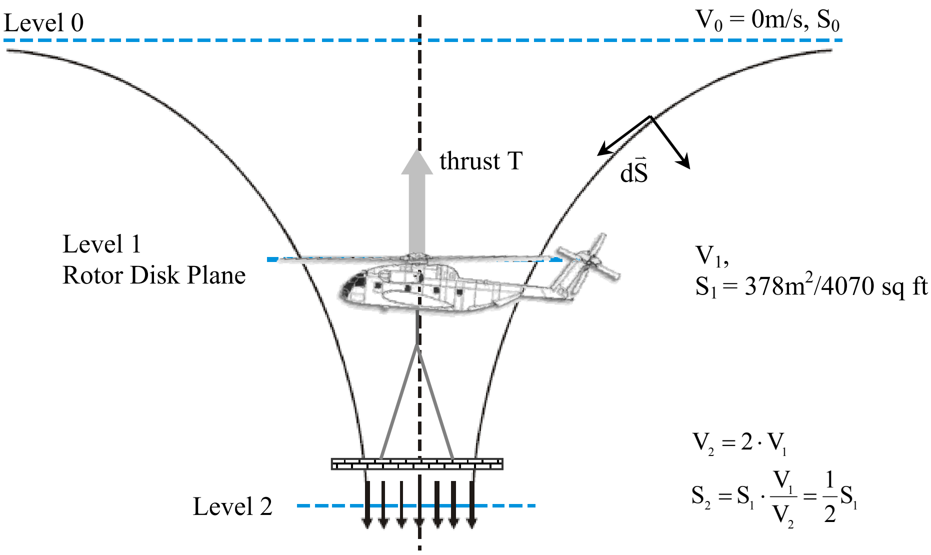

Figure 7: Momentum Theory

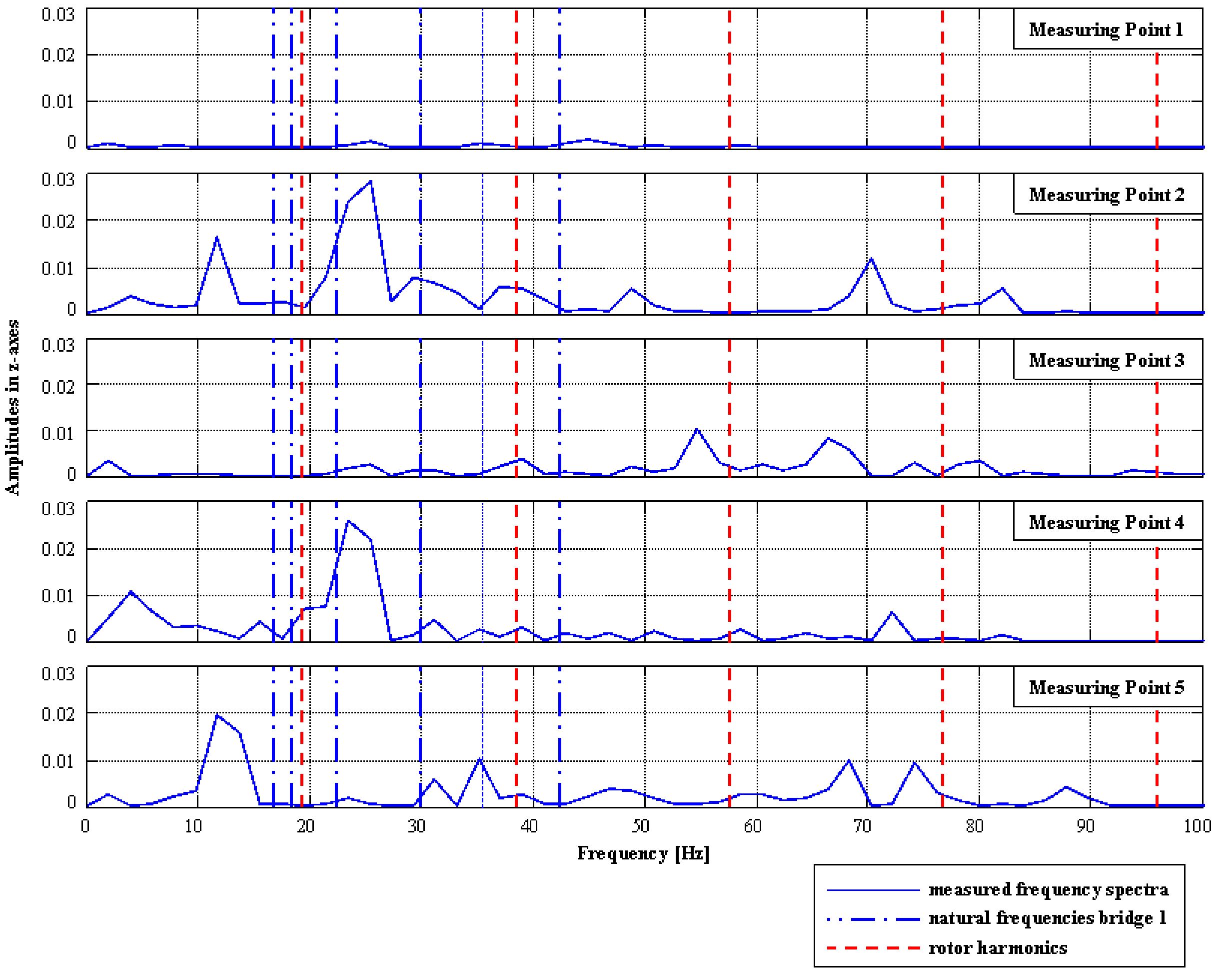

Figure 8: Frequency spectra of the measuring points at bridge 1 in z-axes

Figure 9: Bridge 1 at 50 KIAS forward flight

Figure 10: Bridge 3 in manoeuvre flight

Figure 11: Bridge 3 - precise positioning

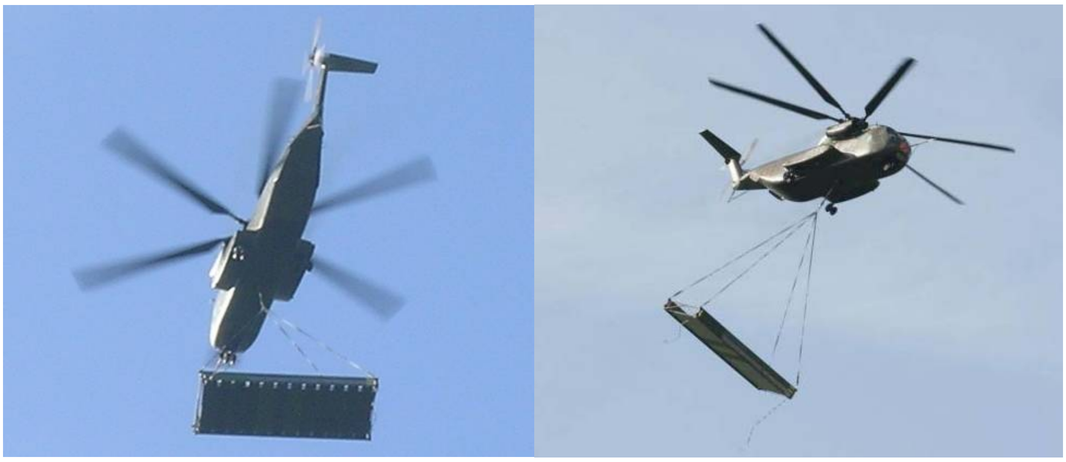

Figure12: Bridge 2 at 40 KIAS

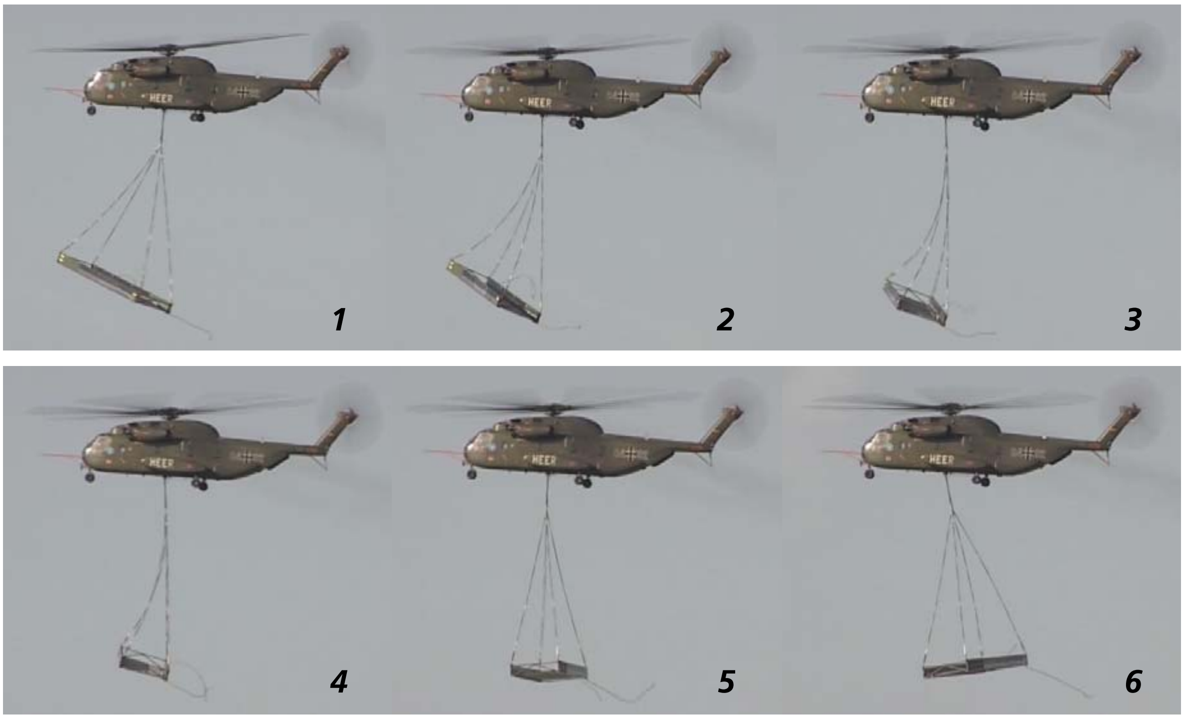

Figure 13: Image series of cable bounce due to load aerodynamic activity at 20 KIAS