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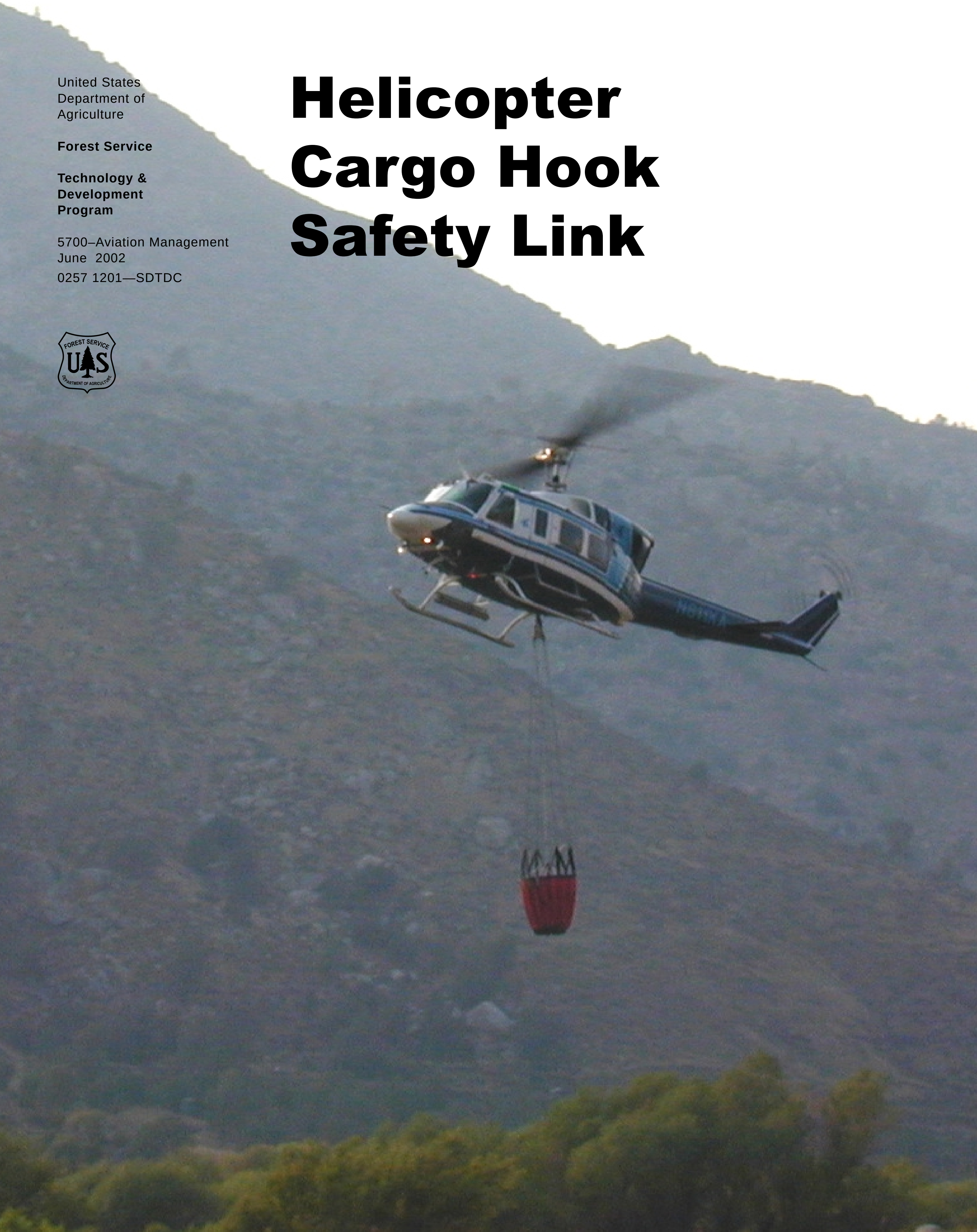
Helicopter Cargo Hook Safety Link



Helicopter Cargo Hook Safety Link

Carl Bambarger–Aviation Program Leader
San Dimas Technology & Development Center

John Seevers
Phoenix Design Engineering

USDA Forest Service

San Dimas Technology & Development Center
San Dimas, CA 91773

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Introduction

In an effort to increase the safety of helicopter long line operations, San Dimas Technology and Development Center (SDTDC) investigated the feasibility of including a frangible link in series with the cargo hook that deliberately releases the long line if the load exceeds the capacity of the helicopter. See figure 1.

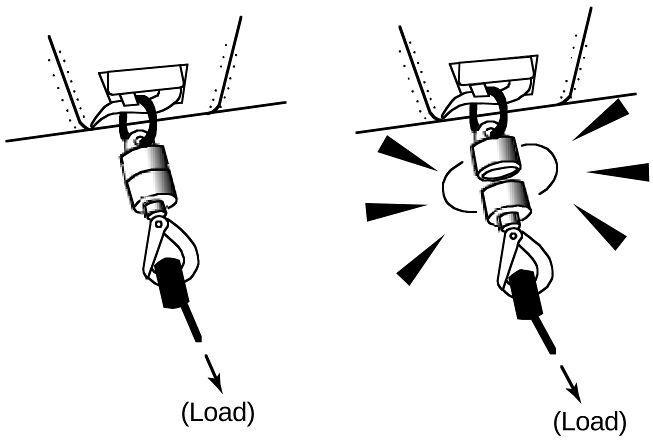

Figure 1—A frangible link in series with a cargo hook deliberately releases the long line if the load exceeds the design capacity of the link.

Four different loading scenarios exist that could create excessive forces in the system:

(1) the long line snags something while the helicopter is cruising.

(2) the gross weight exceeds the lifting capabilities of the helicopter.

(3) in placing or lifting the load it snags on a terrestrial object.

(4) a dynamic factor is imparted to the load. If the load exceeds a preset value, the frangible link separates into two parts and the load releases from the helicopter, thereby preventing damage to the helicopter.

The frangible line concept is commonly used in many systems to protect valuable pieces of equipment by deliberately including a weak member or “fuse” in series with the load. Shear pins, hydraulic relief valves, and electrical fuses are a few examples in common use.

Background

Relevant background material for long line-associated problems can be gathered from basic helicopter flight principles and limitations, operating environments or conditions that can cause problems, incident histories, and the Federal Aviation Administration (FAA).

If the weight of the helicopter plus the load exceeds the lift that the helicopter can generate at the time a pickup is being made, there will be a problem. Typical reasons for this situation are excessive weight on the long line and/or too high density altitude. The first reason is straightforward: too much weight was placed on the long line. This problem is classified as human error where proper attention was not paid to the loading. The second reason—density altitude caused by a combination of hot temperatures, humid conditions, and high altitude—is more subtle and adversely affects the lifting ability of the helicopter in two ways. First, the less dense air means that the aerodynamic lift that can be generated by the rotor is reduced. Secondly, the power generated by the engine at high density altitudes is also less. Therefore, high density altitudes pose a double threat to lifting heavy loads.

The case in which the load snags on a terrestrial object while lifting or placing items, the developed load on the safety link is analogous to an overloaded condition described in the first reason above. In both conditions the onset of the load is gradual. By contrast, when the long line strikes a stationary object while the aircraft is in forward flight, the onset of the load is extremely rapid. Therefore, these two conditions (snags and overload) will be considered one design scenario for the rest of this report.

Maneuvering or turbulence can cause dynamic loads. High-maneuvering “g” forces are caused by abrupt changes in attitude such as a severe pull up, or by a steep turn. Turbulent dynamic loads are caused by wind shears in unstable meteorological conditions.

If the long line strikes an immovable object during lifting operations or during forward flight, the forces in the long line can become very large, very fast. If a large additional force is applied to the long line, an incident will likely result.

Most of the hooks in the field today were FAA certified to release at the hook-rated capacity. Prior to 2000 there was no requirement that the hook be capable of releasing at a load greater than the rated working load. This means that if the load exerted on the hook becomes greater than the rated capacity, it is not certified to release. This also means that even if the pilot recognized that the long line had snagged, the increase in load might exceed the capacity of the hook and jam it, preventing it from being released manually. A frangible member installed in this system could prevent an incident under this set of loading circumstances.

A review of incident histories is useful for determining the frequency of incidents and how serious they were. By studying incidents, conclusions can be drawn regarding whether enough incidents exist to justify developing new hardware and what new hardware might prevent these incidents.

The regulatory position of the FAA needs to be considered whenever anything related to aircraft is proposed.

Relevant Incident History

SDTDC reviewed the SAFECOM database through 1999 data to document problems that were coded as related to long lines. The review found that of 109 reported total incidents, 28 were coded as a long line mission. Of these 28, only 2 were coded as long line strikes. One of these resulted in a safe landing with no injuries, while there was a fatality in the other. From the database, 23 fatalities are recorded from 109 incidents with only 1 attributed to a long line strike.

FAA Involvement

As with all flight hardware, it is essential that a frangible link be in compliance with appropriate FAA regulations and policies. Some confusion and disagreement exist within the FAA regarding the appropriate regulations since we are dealing with a "disposable load." The general opinion of field offices, as well as manufacturers, is that there are no design regulations for disposable loads. No manufacturer of items that are suspended from the cargo hook have applied for or obtained any kind of type certificate or other authorizing document. In general, the installation of an accessory on the cargo hook does not require a supplement to the flight manual, nor an FAA Form 337. The FAA Fort Worth office disagrees with this interpretation and cites the definition of External Load Attaching Means found under CFR 1.1. External Load Attaching Means is defined as: "The structural components used to attach an external load to an aircraft, including external-load containers, the back-up structure at the attachment points, and any quick release device used to fettison the external load." This is interpreted to mean everything down to and including the load. Also the following regulations contain information pertinent to helicopter long line operations: CFR 27.337, 27.339, 27.341, 27.865, particularly sections b.1 and b.3; 29.337; 29.339; 29.341; and 29.865. Part 27 governs Normal Category Rotorcraft and Part 29 governs Transport Category Rotorcraft. The wording in these two parts is exactly the same with two exceptions. Paragraph .341 in Part 27 specifies vertical gusts and in Part 29 it specifies vertical and horizontal gusts. Part 29.865 section c adds item 6, which deals with one engine inoperative operations with human external cargo. Since these differences are not relevant to the frangible link issue, the text of Part 29 is provided and will be used to review the position of the FAA.

"§ 29.337 Limit maneuvering load factor.
The rotorcraft must be designed for –

(a) A limit maneuvering load factor ranging from a positive limit of 3.5 to a negative limit of -1.0; or

(b) Any positive limit maneuvering load factor not less than 2.0 and any negative limit maneuvering load factor of not less than -0.5 for which –

  (1) The probability of being exceeded is shown by analysis and flight tests to be extremely remote; and

  (2) The selected values are appropriate to each weight condition between the design maximum and design minimum weights."

"§ 29.339 Resultant limit maneuvering loads.
The loads resulting from the application of limit maneuvering load factors are assumed to act at the center of each rotor hub and at each auxiliary lifting surface, and to act in directions and with distributions of load among the rotors and auxiliary lifting surfaces, so as to represent each critical maneuvering condition, including power-on and power-off flight with the maximum design rotor tip speed ratio. The rotor tip speed ratio is the ratio of the rotorcraft flight velocity component in the plane of the rotor disc to the rotational tip speed of the rotor blades, and is expressed as follows:

$$\mu = V \cos \alpha / (\Omega R)$$

where –
V = The airspeed along the flight path (f.p.s.);
α = The angle between the projection, in the plane of symmetry, of the axis of no feathering and a line perpendicular to the flight path (radians, positive when axis is pointing aft);
Ω = The angular velocity of rotor (radians per second); and
R = The rotor radius (ft.)."

"§ 29.341 Gust loads.
Each rotorcraft must be designed to withstand, at each critical airspeed including hovering, the loads resulting from vertical and horizontal gusts of 30 feet per second."

"§ 29.865 External loads.
(a) It must be shown by analysis, test, or both, that the rotorcraft external load attaching means

for rotorcraft-load combinations to be used for nonhuman external cargo applications can withstand a limit static load equal to 2.5, or some lower load factor approved under §§ 29.337 through 29.341, multiplied by the maximum external load for which authorization is requested. It must be shown by analysis, test, or both that the rotorcraft external load attaching means and corresponding personnel carrying device system for rotorcraft-load combinations to be used for human external cargo applications can withstand a limit static load equal to 3.5 or some lower load factor, not less than 2.5, approved under §§ 29.337 through 29.341, multiplied by the maximum external load for which authorization is requested. The load for any rotorcraft-load combination class, for any external cargo type, must be applied in the vertical direction. For jettisonable external loads of any applicable external cargo type, the load must also be applied in any direction making the maximum angle with the vertical that can be achieved in service but not less than 30°. However, the 30° angle may be reduced to a lesser angle if —

(1) An operating limitation is established limiting external load operations to such angles for which compliance with this paragraph has been shown; or

(2) It is shown that the lesser angle can not be exceeded in service.

(b) The external load attaching means, for jettisonable rotorcraft-load combinations, must include a quick-release system to enable the pilot to release the external load quickly during flight. The quick-release system must consist of a primary quick release subsystem and a backup quick release subsystem that are isolated from one another. The quick release system, and the means by which it is controlled, must comply with the following:

(1) A control for the primary quick release subsystem must be installed either on one of the pilot's primary controls or in an equivalently accessible location and must be designed and located so that it may be operated by either the pilot or a crewmember without hazardously limiting the ability to control the rotorcraft during an emergency situation.

(2) A control for the backup quick release subsystem, readily accessible to either the pilot or another crewmember, must be provided.

(3) Both the primary and backup quick release subsystems must –

(i) Be reliable, durable, and function properly with all external loads up to and including the maximum external limit load for which authorization is requested.

(ii) Be protected against electromagnetic interference (EMI) from external and internal sources and against lightning to prevent inadvertent load release.

(A) The minimum level of protection required for jettisonable rotorcraft-load combinations used for nonhuman external cargo is a radio frequency field strength of 20 volts per meter.

(B) The minimum level of protection required for jettisonable rotorcraft-load combinations used for human external cargo is a radio frequency field strength of 200 volts per meter.

(iii) Be protected against any failure that could be induced by a failure mode of any other electrical or mechanical rotorcraft system.

(c) For rotorcraft-load combinations to be used for human external cargo applications, the rotorcraft must –

(1) For jettisonable external loads, have a quick-release system that meets the requirements of paragraph (b) of this section and that –

(i) Provides a dual actuation device for the primary quick release subsystem, and

(ii) Provides a separate dual actuation device for the backup quick release subsystem;

(2) Have a reliable, approved personnel carrying device system that has the structural capability and personnel safety features essential for external occupant safety;

(3) Have placards and markings at all appropriate locations that clearly state the essential system operating instructions and, for the personnel carrying device system, ingress and egress instructions;

(4) Have equipment to allow direct intercommunication among required crewmembers and external occupants;

(5) Have the appropriate limitations and procedures incorporated in the flight manual for conducting human external cargo operations; and

(6) For human external cargo applications requiring use of Category A rotorcraft, have one-engine-inoperative hover performance data and procedures in the flight manual for the weights, altitudes, and temperatures for which external load approval is requested.

(d) The critically configured jettisonable external loads must be shown by a combination of analysis, ground tests, and flight tests to be both transportable and releasable throughout the approved operational envelope without hazard to the rotorcraft during normal flight conditions. In addition, these external loads – must be shown to be releasable without hazard to the rotorcraft during emergency flight conditions.

(e) A placard or marking must be installed next to the external-load attaching means clearly stating any operational limitations and the maximum authorized external load as demonstrated under § 29.25 and this section.

(f) The fatigue evaluation of § 29.571 of this part does not apply to rotorcraft-load combinations to be used for nonhuman external cargo except for the failure of critical structural elements that would result in a hazard to the rotorcraft. For rotorcraft-load combinations to be used for human external cargo, the fatigue evaluation of § 29.571 of this part applies to the entire quick release and personnel carrying device structural systems and their attachments."

As related to a separating link, paragraph 337 establishes the positive limit load factor at 3.5 for the rotorcraft with an exception clause that might allow as low as a 2.0 design limit load factor. Paragraph 339 states that the limit load factors are applied at the center of the load and act in the critical direction. Paragraph 341 pertains to gust loads.

Paragraph 29.865 (a) requires that the external attaching means for nonhuman external cargo must withstand a limit static load equal to 2.5 times the authorized external load, unless a value less than 2.5 is approved for the rotorcraft under paragraph 337. The minimum static load factor could be as low as 2.0 under this exception. Therefore, this paragraph requires that the frangible link must have a static load factor of at least 2.0.

Paragraph 29.865 (b) requires that for jettisonable cargo the attaching means must include a quick release system to enable the pilot to release the external load. Section (b.1) also states that the quick release system must be installed so that it may be operated by the pilot or crewmember. This requirement can be interpreted to mean that the pilot must take an action to release the load and precludes the use of an automatic control system that would function without the release command of the pilot. Section (b.3) states that the quick release system should function up to the maximum load for which approval is being sought. This combined with the 2.5 g load factor means that the fuse device must not fail at less than 2.5 times the maximum working load. For example, a 3,000-pound working load requires that the "fuse" not fail at less than 7,500 pounds. This requirement means that the fuse cannot protect the helicopter from attempting to lift loads that exceed its limits for a given set of flight parameters. This affords no protection for density altitude or combined weights of helicopter and external load that only modestly exceed lifting capabilities.

Design Requirements

An ideal device or system improves the safety of all phases of long line operations. Additionally, the implementation of any system must be carefully thought out, so that additional or complex requirements are not added to the tasks of helicopter operation specialists. Finally, the system must be compatible with appropriate FAA regulations.

The design requirements and rationale for each of the three operating environments need to be established.

1. The load exceeds the lifting capabilities of the helicopter.

In this case the combined weight of the helicopter and load exceeds the lift that the helicopter can generate. Several factors can contribute to this situation, and the combined result of all of these factors determines whether a problem exists. The most obvious factor is that the load is too heavy and a lesser payload is appropriate. Weighing the payload and knowing the lift available could resolve this scenario. Density altitude has two contributing factors to limiting the load. First, it decreases the efficiency of the engine, thereby reducing the power available. Secondly, high density altitudes reduce the efficiency of the rotor, further reducing the lift that can be generated. The sum of the load in the helicopter and the load on the hook is the useful load. For a given helicopter, the basic load, including the pilot, oils, standard equipment, etc., does not vary significantly during the course of a mission; however, the fuel on board does vary. As a result, for a given density altitude, the maximum load that can be applied to the hook and have a successful lift is dependent on the consumable amount of fuel remaining on board, which is varying. The margin between operating effectively and safely and not being able to make a lift is very small, probably less than 50 pounds.

The parameters described above point to two major problems with a breakaway link to protect against lifting overloads. First, there needs to be some form of compensating mechanism for density altitude; and secondly, to maximize cost efficiency, there needs to be a compensation for actual weight of the helicopter at the time. Additionally, the basic weight of each helicopter and flight crew will be different. The breakaway point will need to be modified or set for each helicopter each day. This alone means that the device must be adjustable and needs to be calibrated. Logistically this is difficult to document, calibrate, and install.

Since the helicopter operates at different density altitudes, some form of automatic control is necessary to adjust for this difference. Each of these design criteria adds design and manufacturing costs, logistic difficulties, and complexity; each introduces potential reliability problems, which drives the cost up prohibitively.

2. The long line snags something while the helicopter is cruising.

In this case the long line becomes attached to a fixed object while the helicopter is cruising. The loads in the long line are in excess of seven times the normal load. This excessive load (between the normal and incident mode) provides enough of a window in which to design a reasonable safety link. Considering that the typical ultimate load factor is 3.75, if a safety device were designed to fail with a load factor of 5 plus or minus 1, adequate margins from the usual design of 3.75 and the incident mode of 7 exist. A reliable inexpensive device could be developed using a tension failure, a double shear, or an over-center mechanism to release the load.

3. A dynamic factor is imparted to the load.

Maneuvering or turbulence could impart a dynamic load to the long line. In coordinated flight, a 60 degree bank angle produces a load factor of 2.0; for a 3.75 load factor to exist, the bank angle must be 75 degrees.
Load factors would have to exceed 3.75 g's to cause structural damage to the helicopter and no incident data was found where this occurred. At factors less than 3.75, the helicopter would accelerate in the direction of the g load, vertically downward being the worst case.

A significant loss of altitude would not occur suddenly from dynamic loads. Basic equations of dynamics state:

$$s = 1/2 \ a \ t^2 \qquad (1)$$

where **a** is the acceleration and **t** is the time to cover the distance **s**. If the acceleration was 3.75 g's or 121 feet/second/second, it takes 2.9 seconds to lose 500 feet. With this amount of time, the pilot could react and release the load.

Basic Passive Design Concepts

The concept is to attach a passive device to the cargo hook of the helicopter and then attach the accessory to the bottom of the device placing the frangible link in series with the external load. The passive device requires no external command or signal to release the load. If the load exceeds the preset value, the device separates and the load releases from the helicopter. Consequently, the helicopter is not tied via the cargo hook to a load that exceeds its capacity. This device is beneficial if the external load were excessive or if the accessory became entangled with an immovable object, such as the ground. Usual methods employed to separate mechanical mechanisms are failure elements or over-center devices. A failure element can be in tension, shear, or double shear. An over-center device is one in which, after a certain amount of deflection, a mechanical member toggles from one position to another, with the first position carrying the load and the second being a released status. The three concepts investigated for the cargo hook were double shear failure; tension failure; and a ball-spring over-center mechanism. All devices operate using the principle that they remain intact at loads up to and including the design limit but release at loads exceeding that limit.

The device in figure 2 is a double shear failure fixture in which a pin will be sheared in two places for failure. The cross-sectional area and the material of the pin dictate the load required for separation. Because of a limited number of acceptable materials from which to manufacture the shear pins, different release load ratings require different diameter pins and hence different fixtures. The greater the number of different release load ratings required, the greater the inventory of devices needed. This creates a logistics problem for field operations. If different load ratings were achieved via different pin materials with the same diameter, operational personnel would insure sure the correct pin was installed for each application.

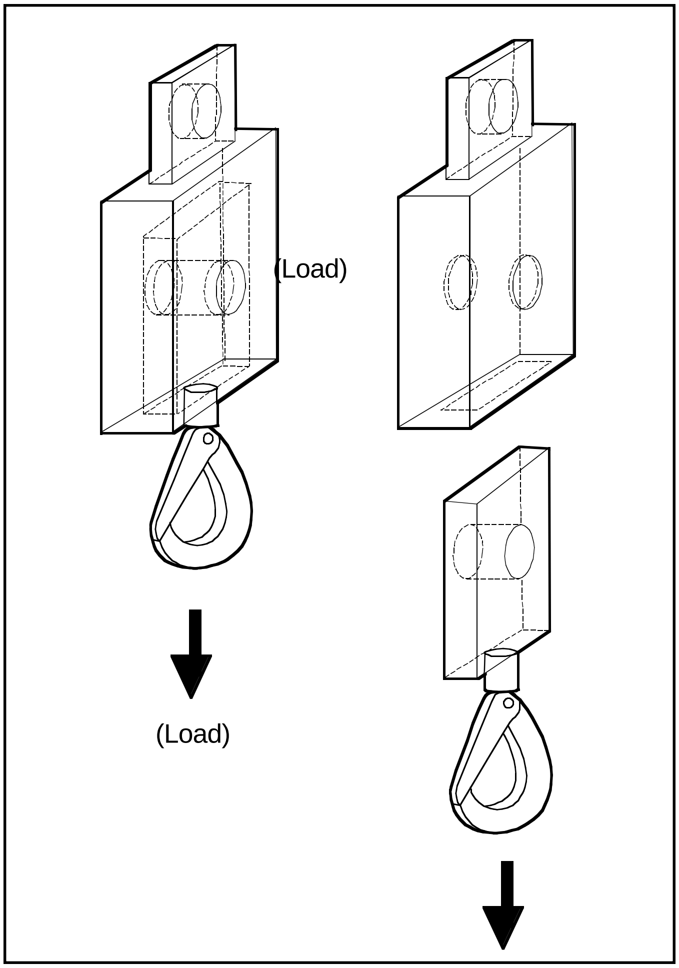

Figure 2— Shear pin design.

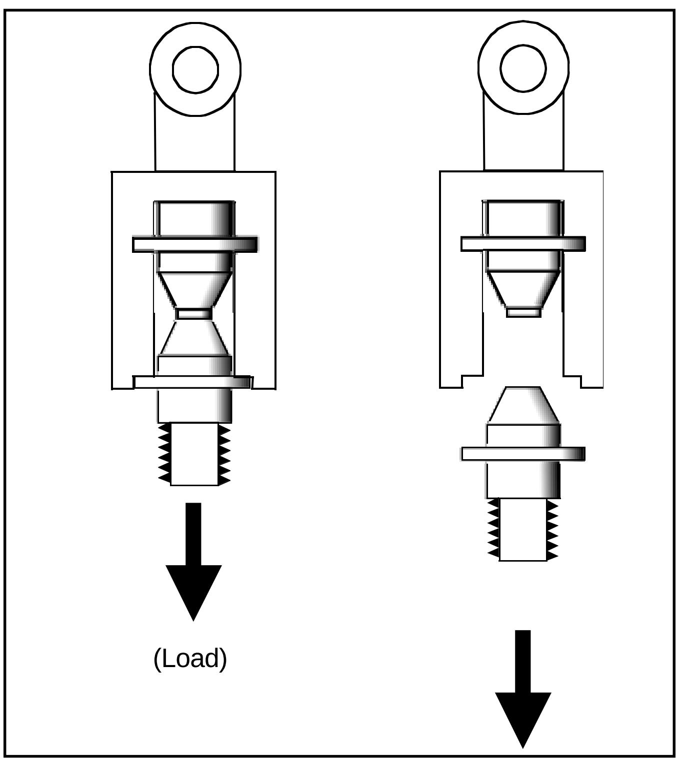

Figure 3—Tensile design.

The device in figure 3 is a tension failure release fixture in which the failure member is very similar to engineering test coupons used to establish the strength properties for a given material. Tensile stress is defined as the force divided by the area or

$$\sigma = F / A$$

When this stress exceeds the ultimate strength of the material, the material fails. For a given material the cross-sectional area dictates the ultimate load of the device. Different materials and different cross-sectional areas could be used in the same fixture, allowing the same basic fixture to be used for different load ratings. Care must be exercised to make sure that the correct insert were in place to achieve the desired release load. This can be done by color coding the inserts and having them visible through a window. Labeling is critical to achieve satisfactory results in the field.

When new, both the double shear and tension failure devices should have a field release load consistency of ± 5 percent from the rated load. Although the new accuracy of these devices is good, with use, the accuracy over time could deteriorate because of the effects of fatigue. If the applied working loads are a significant percent of the ultimate strength of the failure members and the loads are repeatedly applied, fatigue failures are likely. Fatigue failures occur at stresses that are significantly less than the ultimate strength of the original material. Fatigue failures are based on the magnitude of the alternating stress and the number of cycles at that stress. A cycle is every time the stress becomes that level and could be many cycles on a single flight because the load could be bouncing or vibrating. Counting the number of cycles at a given stress is an unmanageable task. Consequently, both the double shear or tension failure element designs have a limitation on being able to accurately and consistently releasing at a predetermined value. Most mechanisms that use shear pins as safety links are basing the safety on the fact that the critical load will greatly exceed the normal operating loads for the system, and that the normal operating loads are not large enough to initiate a fatigue failure.

Shear or tension failure members are suitable for ground snagging while in forward flight situations because of the large gap between normal operation and incident situations but they are not suitable for lifting problems because of the narrow margin between normal operation and problem situations.

One example of an over-center mechanism is the compression spring-ball mechanism shown in figure 4. In this design, a spring or springs presses a ball into a detachable grooved part. When the extraction force is great enough to overcome the force imparted by the ball and spring, the suspended load is released from the spring body housing. The concept is similar to the release principle used in common snow ski bindings. This design has several advantages over the failed member concept. The device is reusable without introducing a replacement element, thereby eliminating a logistic problem associated with correct spare parts. Components can be designed so that the stress is below the fatigue endurance limit, eliminating the uncertainties associated with fatigue failures. External contamination could be disastrous, however, and must be prevented from entering the separating parts or the spring-ball mechanism. An external boot is an acceptable solution to this problem. Wear of the sliding parts, ball, and ball seat will affect the accuracy and consistency of the release load. Using hard-surfaced components should minimize the effects of wear, but a remove-and-inspect policy still needs to be implemented. As with the shear and tension failure designs above, this concept works well for the snagging cruise problem but has accuracy problems for excessive load lifts because of the narrow margin.

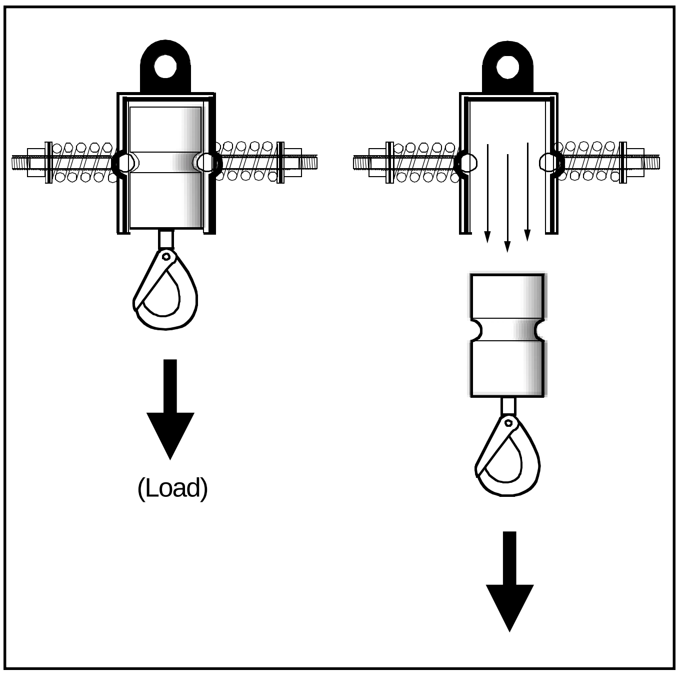

Figure 4–Compression spring-ball design.

Good, reliable, and cost-effective designs can be engineered using any of the three concepts discussed above; that is, double shear failure, tension failure, or a spring-loaded mechanism. An accuracy and consistency of ± 10 percent, or better, of a desired value can be economically achieved. For a 3,000 pound long line load, however, an accuracy of ± 1 percent is necessary to provide protection for the lifting environment type of problem. The spring-ball design is easiest to change the release value, and can be accomplished by merely changing the preload on the spring. The tension failure is the next easiest to change the release value and can be accomplished by inserting a different cross-sectional area coupon as the failure element. Realistically, to have different release loads with the double shear design requires different fixtures. The member failure designs are less expensive to manufacture, but after releasing, are more costly and troublesome to put back together. An added problem with the failure designs is the logistics and personnel issues of reinstalling the correct replacement member after a separation occurs. No passive concept is well suited to small changes in the acceptable operating environment caused by density altitude or consumables of the helicopter.

Advanced Design Concepts

Nonpassive release mechanisms include pilot-induced releases and those employing some form of automatic control. Since the pilot already has the ability to release the cargo hook, adding an additional pilot-induced mechanism is redundant and costly, and it undermines the premise that a device is desired that will release the load without pilot intervention.

An automatic control device is very attractive because it could compensate for density altitude, load, helicopter lift, forward airspeed, and more. It is significantly more complex than any of the basic designs, and the cost of designing and manufacturing such a device is likely be two or more orders of magnitude greater than the basic designs. Because the system is more complex, reliability also becomes an issue. It does not appear that the difficulties associated with an automatic device are warranted by the potential advantages.

Requirements on Field Personnel

Any safety frangible mechanism requires additional procedures and maintenance by field personnel. Because of the fatigue issues associated with shear or tensile failure members for a design to provide protection in the lifting phases of flight, the failure elements needs to be tracked with regard to loading usage. To accomplish this, each pin or element is serialized. When placed into the fuse body, the number of cycles needs to be recorded for that serialized part. When that part receives the number of cycles allowed by the design, it must be retired and destroyed. Counting the number of cycles is a formidable task itself. Since turbulence or maneuvering can create multiple fatigue cycles on a single lift, either a load-counting device needs to be incorporated or a time-to-replace schedule needs to be established. If a time-to-replace schedule is used, data needs to be gathered to support a replacement schedule. If a counting device is used, the counter itself is an additional piece of equipment that needs to be designed and maintained.

Analysis

In the lift-snagging event, the onset of the increasing load on the hook is controlled by the lifting capacity of the helicopter at the density altitude. Assuming the lift is vertical and using the basic dynamics equation F = M * a,

$$L - W_T - S = M_T * a_y \qquad (2)$$

where L is the helicopter lift, W_T is the total weight of the helicopter and load, S is the force on the load caused by the snag, M_T is the total mass of the helicopter and load, and a_y is the vertical acceleration. If it is assumed that the vertical acceleration is constant in normal lifting operations, kinematic equations state that the $a_y = (v_2 - v_1) / Dt$. If it is assumed that the vertical motion of the helicopter goes from rest to 100 fpm in 1 second,

$$a_y = 1.7 \text{ ft/sec/sec} = 0.05 \text{ g}$$

Substituting back into equation 2 for normal operations with S = 0, it is found that the lift equals 1.05 times the weight of the helicopter and load. If during the lift the load becomes snagged and the lift remains the same, equation 2 becomes

$$S = W_T * (0.05 - a_y / g) \qquad (3)$$

a_y will be negative since the acceleration of the helicopter will be toward the ground.
By examining a free body diagram of just the load, it is found that

$$F - W_L - S = M_L * a_{yL} \qquad (4)$$

where F is the force in the long line, W_L and M_L are the weight and mass of the load, and a_{yL} is the acceleration of the load. Kinematic equations state

$$a * s = 1/2\, v_2^2 - 1/2\, v_1^2 \qquad (5)$$

where a is the acceleration, s is the distance over which the acceleration a occurs, v_2 is the final velocity, and v_1 is the initial velocity. Just before the snag occurs, the helicopter velocity is v_1 and after the snag has stopped the helicopter, the velocity is 0. Using equations 1, 3, 4, and 5, table 1 was developed. It relates the long line load factors and time to stop as functions of vertical speed and stopping distances. The distance is the distance the helicopter travels to come to a complete stop, a_y is the average vertical acceleration, the time is the time to go from the vertical speed v_{1y} to rest, S is the average force on the snag, F is the force in the long line, and "F / W_L" dynamic load ratio on the long line, "g" load. Tables 1 and 2 assume the helicopter weighs 6,000 pounds and the load is 3,000 pounds.

In the case where the long line snags an object when the helicopter has a significant forward velocity, the helicopter essentially pivots about the snag point going from a horizontal velocity in an arc to a vertical velocity at impact with the ground. The equation for the velocity v_2 at any point on this arc is given by

$$v_2 = [\, 2\, \rho\, g\, (\, 1 - \cos\theta\,) + v_1^2]^{1/2} \qquad (6)$$

where θ is the angle at which the nose of the helicopter is below the horizontal, where v_1 is the horizontal velocity before the snag, v_2 is the vertical velocity at the angle q, and ρ is the length of the long line. Equation 6 applied to the case for impact with the ground yields

$$v_2 = [\, 2\, \rho\, g + v_1^2]^{1/2} \qquad (7)$$

where v_2 is the vertical velocity at ground impact. The force in the long line at impact is given by

$$F = L + 2 * W_H + W_H * v_1^2 / (\rho * g) \qquad (8)$$

where W_H is the weight of the helicopter. The approximate time for the helicopter to make the transition from normal horizontal flight to impact is given by

$$\Delta t = \pi * \rho / (v_1 + v_2). \qquad (9)$$

Table 1—Accelerations with Vertical Lift at Hover

v_{1y} (fpm)	v_{1y} (fps)	Distance (ft)	a_y (ft/s/s)	a_y (g's)	Time (s)	S (lb)	F (lb)	F/W_L
10	0.17	1	-0.01	0.000	12	454	3,453	1.2
10	0.17	2	-0.01	0.000	24	452	3,451	1.2
100	1.67	0.25	-5.56	-0.173	0.3	2,003	4,485	1.5
100	1.67	0.5	-2.78	-0.086	0.6	1,226	3,968	1.3
100	1.67	1	-1.39	-0.043	1.2	838	3,709	1.2
100	1.67	2	-0.69	-0.022	2.4	644	3,579	1.2
500	8.33	1	-34.72	-1.078	0.24	10,155	9,920	3.3
500	8.33	2	-17.36	-0.539	0.48	5,302	6,685	2.2

The vertical components of the velocity and acceleration are

$$v_y = v * \sin\theta \quad (10)$$

and

$$a_y = a * \sin\theta \quad (11)$$

For an initial horizontal velocity of 60 mph, which equals 88 fps, equation 6 gives the forward velocities at 30, 60, and 90 degrees as 93, 105, and 119 fps, respectively. For an object traveling on a circular path, additional kinematic equations are

$$\Delta\theta = \omega_{avg} * \Delta t \quad (12)$$

and

$$\rho\ \omega_{avg} = 1/2\ (v_1 + v_2) \quad (13)$$

where ω_{avg} is the average angular velocity and Δt is the time for the nose angle $\Delta\theta$ to occur. For a helicopter initially traveling horizontally at 60 mph and becoming snagged, the time to travel from a nose down angle of 30 degrees to 60 degrees according to equations 12 and 13 is only 0.530 seconds.

At a nose down angle of 60 degrees the helicopter has a vertical velocity component by equation 10 of 91 fps. If at this point the pilot has released the long line and is attempting to pull up, in order to avoid hitting the ground his average vertical acceleration given by equation 5 must be greater than 82 ft/sec/sec. Equation 11 then states that the total acceleration must be 164 ft/sec/sec, or 5.1 g's. The acceleration as in equation 11 exceeds the structural strength of the helicopter.

Table 2 relates the time to crash and long line load factors as a function of the forward speed. As in table 1, F / W_L is the load factor in g's. Figure 5 illustrates the force caused by snagging load.

Table 2—Snag Data with Forward Speed

v_1 (mph)	v_1 (fps)	v_2 (fps)	Time (s)	F (lb)	F/W_L
10	14.7	82	3.26	21,851	7.3
30	44.0	92	2.32	25,057	8.4
60	88.0	119	1.52	35,880	12.0
100	146.7	167	1.00	61,533	20.5

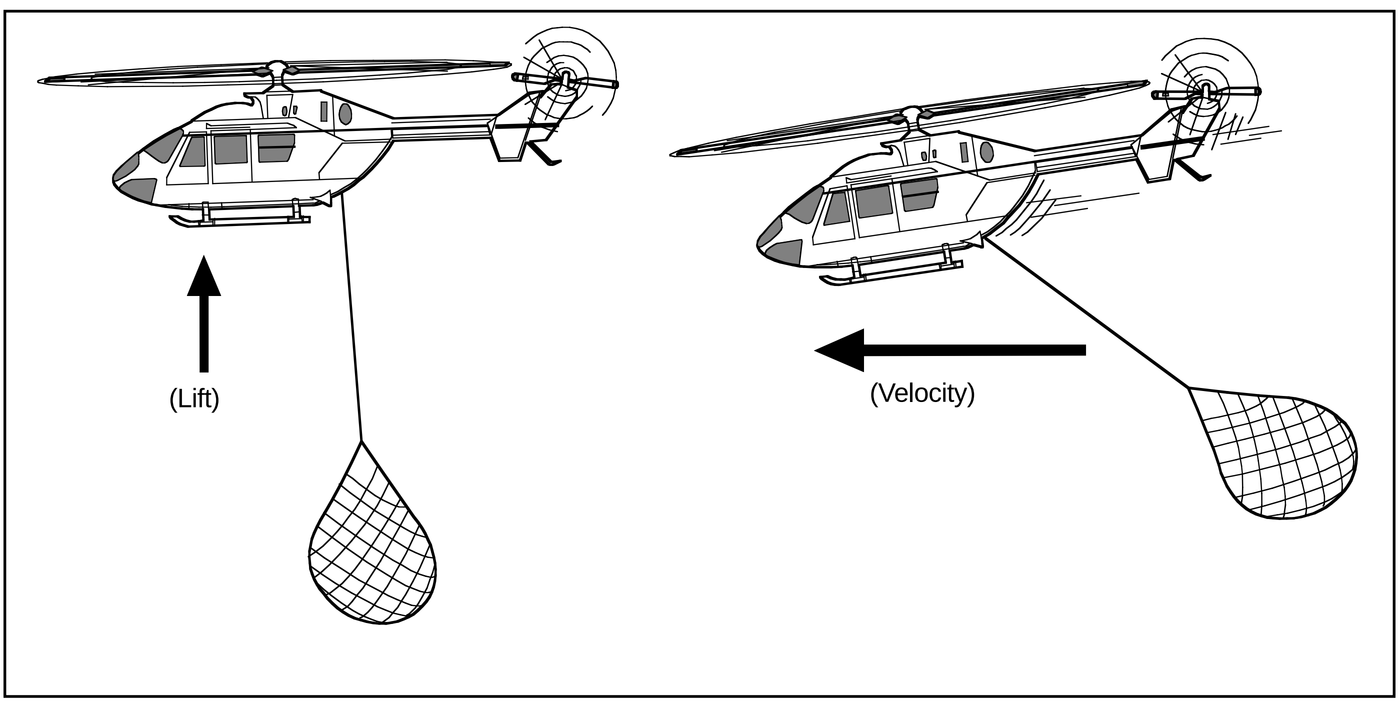

Figure 5—Force caused by snagging load.

Discussion

The basic concept of a frangible link appears to be in conflict with several requirements in FAA regulations. First, the FAA requires the pilot to have control over the disposable load, and the fundamental premise of this proposed device is that the pilot does not have to act to release the load. Secondly, an FAA regulation states that the design strength must exceed the load factor times the working load limit. This requirement completely eliminates any possibility of employing a device that releases just a little above the normal lift load as is required for density altitude, slight excessive overload, or a snag encountered while lifting in hover.

A reliable safety mechanism can be designed and manufactured to perform the basic function of load separation. Design criteria that meet the needs of both hover lift problems and forward flight snag problems, however, are all essentially mutually exclusive. The very narrow margin between normal operations and incident for hover lifting makes the design and manufacture of a device very precise and very expensive. An additional difficulty is that the release force needs to be adjustable for different empty helicopter weights, available engine power, different consumables on board at the time of lift, and different density altitudes. Without some form of automatic control that has these inputs, a satisfactory device cannot be developed for the hover lifting scenarios. An automatic control device adds major complexity and cost, and therefore is not practical.

Acceptable reliability can be achieved for any of the designs presented here. The problem regarding reliability is when the operating margin becomes very narrow, to have high reliability requires high costs. Also for a more complex automatic control system to achieve high reliability the cost will be higher. Reliable and reproducible results for hover lifting can be obtained, but at very high costs; and the system has to deal with the variability of the operating environment.

Because of the large margin between normal operation and incident, the forward flight safety link is much more feasible. Any of the basic designs presented will work reliably at a reasonable cost. For this application, the double shear design is probably the most economical, followed by the tensile failure design, providing only a few different load settings are required. These two designs are also less complex than the over-center device. Any device has to be protected from environmental conditions such as dirt, dust, water, and chemicals. Because different devices or settings are required for different helicopters and different missions, an operator has to perform a function to have the device have the proper setting. By this adjustable nature, operator error is possible, which introduces another set of problems. Any device requires additional maintenance, logistics, and recordkeeping by field personnel. Training is required to ensure that a proper device and failure setting are installed for a given mission. Inspections and replacement tasks are performed, and with any device, a potential exists to have an improperly sized failure member installed on a given mission.

To perform the above analysis, a number of assumptions and estimates were made. The results should not be construed to be accurate numerical values, but rather to suggest trends and relative magnitudes. In the hover mode, the vertical acceleration is small and the lift of the helicopter is not much higher than the combined weight of the helicopter and load. Whether the lift is 1.02 or 1.15 times the weight is immaterial. The numeric values in table 1 are conservative estimates in that the distance to stop after the snag is encountered is probably greater than the 0.25 to 2 feet shown. Therefore, the actual accelerations ay, snag forces S, long line forces F, and ratio of F to weight are lower than those shown in the table. The time to stop would be greater than tabulated values. The results of table 1 show that the time for the incident to occur is relatively large and the load factors are within the design parameters of flight hardware. The time in the table is what is necessary to stop the helicopter's vertical velocity. For an incident to occur, something must happen after the helicopter comes to a zero vertical velocity, and this takes additional amounts of time. Two things are significant here: First, the load factors should not cause a structural failure in the helicopter, and secondly, there is enough time while the event is developing for the pilot to react and manually release the load. Since events happen slowly, a properly trained pilot has adequate time to recognize the problem and react accordingly without an incident. The hover lift overload or snag situation should not jeopardize the safety of the helicopter or crew.

Table 2 addresses the situation in which the helicopter has a significant forward velocity and the long line becomes entangled with an immovable object. At the instant the snag occurs, the helicopter starts traveling in a circular arc in a vertical plane about the fixed point. The radius of the arc is the length of the long line. The shorter the long line, the quicker the incident will occur. Table 2 shows that even at modest forward speeds there is very little time between encountering the snag and the helicopter's crashing to the ground. Traveling forward at 60 mph the total time for the incident is just 1.5 seconds. Because of the nature of the motion of moving on an arc, it is probable that the pilot would be unaware that anything abnormal were happening for the first 10 percent of this time. Then the pilot would have to identify the problem and react to release the load. At this same time the pilot and helicopter would be subjected to 12 g's.

This force alone is enough to have ultimate structural failures in the helicopter. If the helicopter survived the first part of the arc and if the pilot were able to release the load by the time the nose is pointed down 60 degrees, the helicopter would still have to pull 5 g's to avoid striking the ground. Helicopters are not capable of maneuvering at 5 g load factors. This simple analysis confirms what most people already suspect; at 60 mph, if the long line becomes entangled, it is impossible to avoid an incident. For a snag incident to occur, an almost rhetorical question should be asked: Why was the helicopter cruising so low in the first place?

The above analysis shows that two very different incident modes exist. The lifting-in-hover problem involves relatively small load factors and develops slowly enough for corrective action to be taken. The entanglement-while-cruising mode happens very quickly and the loads are enormous.

Conclusions

1. Since there are few documented incidents in the past where the long line caused a flight-endangering safety problem, it is difficult to justify adding an additional and new piece of equipment to the long line system.

2. FAA regulations require that the pilot be in control of all releases of slung loads; that is, no automatic release devices.

3. The necessity of a safety link can not be substantiated for dynamic loading caused by air turbulence since the pilot has adequate time to react and manually release the load.

4. Without employing some form of automatic control, it is impossible to have a device protect the lifting environment where very small changes in helicopter capability caused by density altitude and consumables on board differentiate between a successful operation and an incident.

5. Two different protection devices are needed because the requirements for lift protection are so much different than those for ground snags during cruise.

6. In hover, a properly trained pilot should have adequate time to recognize the problem and react accordingly. The hover lift overload or hover snag situation should not jeopardize the safety of the helicopter or crew.

7. A significant logistics problem would exist to track the critical components, have spares on hand, and perform the necessary inspections and maintenance. This burden would result in errors of implementation, which would create more inadvertent releases and different safety issues.

8. Realistically, a protection device for the hover mode is not feasible.

9. A protection device for cruise entanglements is designable and producable at a reasonable cost. There does not appear to be justification, however, for the trouble of pursuing this concept.

Recommendations

While increased safety for helicopter operations accomplished by natural resource agencies is always the goal, the development of a breaking link for slung loads does not appear to be a proper implementation.