Active Aerodynamic Stabilization of a Helicopter/Sling-Load System

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A general theoretical model is used in order to investigate the possibility of an active aerodynamic stabilization of a helicopter/sling-load system in the case of a single suspension point. The stabilization system includes two vertical aerodynamic surfaces that are located on the external sling load. The incidence angles of these surfaces are varied according to a set of control laws. This study leads to a system that is relatively easy to realize. The input measurements of the load stabilization system (LSS) include the helicopter and sling load lateral/directional angular rates. It is shown that adding a feedback loop that is based on the load lateral acceleration increases further the stability of the whole system. Studies also show that a single rear surface is very efficient and can be used alone. The proposed LSS is capable of stabilizing the system in a wide range of airspeeds, load weights, suspension methods (geometries), and aerodynamic properties of the external sling load.

Introduction

EXTERNAL sling load is a very useful technique of transporting large and heavy loads by helicopters. The combination of a helicopter and a sling load results in some difficulties that may lead, if not treated properly, to fatal accidents.[1] One of the main problems is associated with the instability of the helicopter/sling-load system. This instability is a function of 1) the helicopter and load dynamic and aerodynamic properties, 2) the connection method between the helicopter and the sling load, and 3) the flight condition. References 2 and 3 offer detailed reviews of instability problems. A more recent research is described in Ref. 4, where a list of other more recent publications on the subject may be found.

Different methods have been suggested in the past in order to prevent helicopter/sling-load instabilities.

References 5–8 present studies where the helicopter's original control system elements are used in order to stabilize the helicopter/sling-load system. In this case, the helicopter's automatic flight control system (AFCS) is adapted for the new task. Studies have shown that such systems offer only a limited stabilization capability.

References 9–11 describe studies where different mechanical devices are used in order to move the points of attachment of the suspension slings (to the helicopter fuselage), and to change the length of these slings in order to stabilize the helicopter/sling-load system. Although this method seems to be very powerful in stabilizing the system, it is also very complicated to realize and relatively heavy. This is probably the reason why such stabilizing techniques have not become operational. Other methods that have been investigated in the past include inertial gyroscopic stabilization[12] or jet control (as described in Ref. 13). These methods suffer from several problems when it comes to regular field application (the need for special power sources, weight penalty, control difficulties, etc.). Again, this is probably the reason why the initial studies were not followed by operational systems.

An interesting method of stabilization is presented in Ref. 14. Two vertical aerodynamic surfaces are located on the external sling load. The incidence angles of these surfaces can be varied according to the control system laws. The system is relatively simple and easy to realize. The studies have shown the promising potential of such a system, but these studies suffered from several drawbacks: only the load dynamics were included in the model, ignoring the helicopter dynamics. Moreover, the study was performed for the case of two suspension points. This case is known to be much less problematic compared with the single suspension point case, which is the subject matter of the present study. The theoretical model included only lateral motions, while longitudinal motions and the coupling between them and lateral motions were ignored. There are also different simplifying assumptions, which were used in the model of Ref. 14, that may raise severe doubts about the accuracy of the results. Concerning the feedback system itself (see Ref. 14), a few of the measurements that are used as inputs to the control system are very difficult to accomplish under actual flight conditions.

In the present paper, the case of a single suspension point, known to present the most severe instability problems, will be considered. The coupled all degrees of freedom of the helicopter and the external sling load are taken into account, as well as the elasticity of the suspension system. In order to stabilize the system, two vertical aerodynamic surfaces are installed on the load. Optimal control theory is applied in order to obtain the control laws according to which the aerodynamic surfaces should be activated. The optimal control theory leads to a system that is fairly complicated to realize. Therefore, studies of different, simpler stabilization systems, which are based on the optimization studies, are described. The final recommended stabilization system is relatively simple and easy to realize. It is shown that the proposed stabilization system will be effective for a relatively wide spectrum of external loads (which differ in their inertia and aerodynamic properties) and different suspension geometries (variation of the length of the sling legs, use of extension sling, etc.).

General Description of the Theoretical Model

The helicopter/sling-load system is described in Fig. 1. The coordinates systems (x_H,y_H,z_H) and (x_L,y_L,z_L) are attached to the helicopter and load, respectively, with the origin at the center of mass. (x_e,y_e,z_e) are the earth system of coordinates. The momentary orientation of the helicopter or load systems

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of coordinates relative to the fixed earth system is defined by three Euler angles (ψ_b,θ_b,ϕ_b), where b may be either H or L.

The location of the cargo hook relative to the helicopter center of mass $\boldsymbol{r}_H$, and the location of the top of the sling legs relative to the load center of mass $\boldsymbol{r}_L$, are constant under the present assumptions.

An extension sling, represented by the vector $\boldsymbol{r}_{ss}$, connects the top of the sling legs with the helicopter cargo hook. The elasticity of the extension sling is described as a linear spring.

The unknowns of the problem include:

1) The Euler angles (ϕ_H,θ_H,ψ_H) and (ϕ_L,θ_L,ψ_L);

2) The helicopter and load linear and angular velocities described by their components relative to the H and L systems of coordinates, respectively (There are 12 such unknowns);

3) The three components of the vector $\boldsymbol{r}_{ss}$, using the earth system of coordinates.

In total, there are 21 unknowns. The 21 equations required for the solution are obtained as follows:

1) Each rigid body yields six scalar equations of motion, thus 12 equations are obtained for the helicopter and the load.

2) The relations between the angular velocity components and the time derivatives of the Euler angles yield six more equations (three for the helicopter and three for the load).

3) By applying kinematic principles, associated with the vector $\boldsymbol{r}_{L/H}$ (see Fig. 1), a set of additional three equations is obtained.

A detailed description of the derivation and the final equations can be found in Refs. 4 and 15.

The equations that describe the helicopter/sling-load dynamics are nonlinear. The subject matter of the present paper is the system stability. The question under consideration is whether a certain trimmed flight condition is stable. Thus, the solution procedure involves two stages. First, the trimmed flight condition is calculated. This calculation involves the complete nonlinear system of equations. Then, in order to check the stability, a linear system of equations is dealt with. This linear system is obtained by assuming small perturbations about the previously calculated trimmed flight condition. The small perturbations lead to the following system of equations:

$$[B]\{\dot{x}\} = [A]\{x\} + [G]_H\{\Delta\delta\}_H + [G]_L\{\Delta\delta\}_L \qquad (1)$$

$\{x\}$ is the state vector, which includes the perturbations in the system unknowns and possibly n_{EX} additional dynamic variables. These variables may be associated with unsteady aerodynamics (see Ref. 4), control system dynamics, etc. Thus $\{x\}$ is a vector of order $(21+n_{EX})$. Matrices $[B]$ and $[A]$ are the "inertia" and "dynamics" matrices, respectively. They are square matrices of order $(21+n_{EX})$.

$\{\Delta\delta\}_H$ and $\{\Delta\delta\}_L$ are the vectors of the perturbations in the control variables, of the helicopter and the sling load, respectively. The vectors $\{\Delta\delta\}_H$ and $\{\Delta\delta\}_L$ are of order $n_{\delta H}$ and $n_{\delta L}$, respectively. $[G]_H$ and $[G]_L$ are the control matrices of the helicopter and the sling load. They are of order $[(21+n_{EX})\times n_{\delta H}]$ and $[(21+n_{EX})\times n_{\delta L}]$, respectively.

The matrices $[A]$, $[B]$, $[G]_H$, and $[G]_L$ include inertial and aerodynamic influences. The aerodynamic influences are introduced through aerodynamic stability and control derivatives of the helicopter and the load.

The aerodynamic stability and control derivatives of the helicopter may be obtained from existing data bases (see the following example) or they may be calculated using existing techniques and computer codes of calculating helicopters and sling-load aerodynamics.

It is convenient to describe the vectors of control variables as the sum of two contributions:

$$\{\Delta\delta\}_b = \{\Delta\delta\}_{bp} + \{\Delta\delta\}_{bc}, \qquad b = H,L \qquad (2)$$

$\{\Delta\delta\}_{bp}$ present small perturbations in the control commands, which are the result of a human pilot activity. $\{\Delta\delta\}_{bc}$ presents contributions of the automatic flight control system. Dealing with a linear control system, the following relations are used:

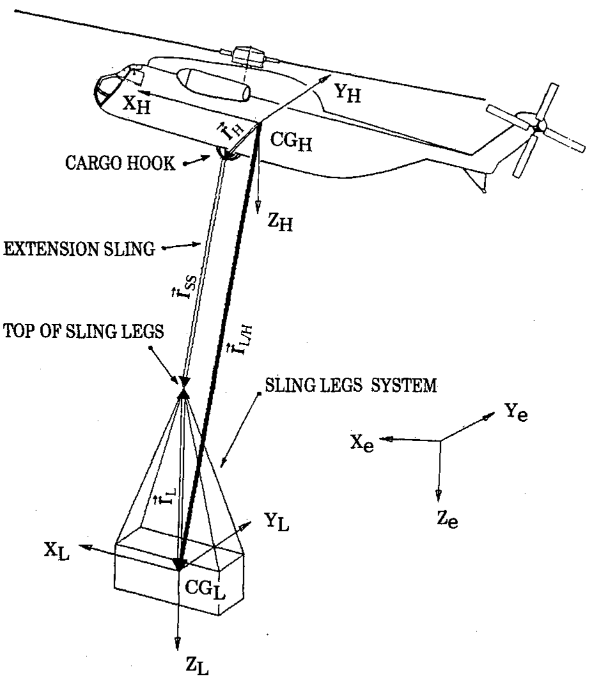

Fig. 1 General description of the helicopter/sling-load system.

$$\{\Delta\delta\}_{bc} = [U_0]_b\{x\} + [U_1]_b\{\dot{x}\}, \qquad b = H,L \qquad (3)$$

$[U_0]_b$ and $[U_1]_b$ are feedback matrices of order $[n_{\delta b}\times(21+n_{EX})]$. The elements of these matrices represent the feedback gains, which are functions of the specific automatic control systems design.

Substitution of Eq. (3) into Eq. (2) and then substitution of the result into Eq. (1) imply that

$$[C]\{\dot{x}\} = [D]\{x\} + [G]_H\{\Delta\delta\}_{Hp} + [G]_L\{\Delta\delta\}_{Lp} \qquad (4)$$

where

$$[C] = [B] - [G]_H[U_1]_H - [G]_L[U_1]_L \qquad (5a)$$

$$[D] = [A] + [G]_H[U_0]_H + [G]_L[U_0]_L \qquad (5b)$$

Equation (4) is the general equation of small perturbations about a certain trimmed flight condition. $\{\Delta\delta\}_{Hp}$ and $\{\Delta\delta\}_{Lp}$ represent small perturbations in the pilot commands, about the finite trimmed flight commands, applied to the helicopter and load, respectively. While investigating the system stability with "fixed stick," $\{\Delta\delta\}_{Hp}$ and $\{\Delta\delta\}_{Lp}$ are taken equal to zero. Thus, Eq. (4) is reduced to a homogeneous system of linear equations. The eigenvalues and eigenvectors of this homogeneous system are indicators of the system stability.

Up to this point the derivations have been general. In the next section, the specific control system of the external sling load is discussed.

External Sling-Load Control System

As is clear from the Introduction, in order to stabilize the helicopter/sling-load system, it is possible to apply the following techniques: use the original helicopter controls, add some control means to the load, or combine the two above possibilities. Since the sling load is the cause of instability (modern helicopters usually have a stability-augmentation system that stabilizes them without the presence of external sling loads), it seems reasonable that it would be more effective to try and apply control means directly to the cause of instability—the external sling load. Studies have supported this reasoning.

The load control will be achieved by installing controllable aerodynamic surfaces on the load. It is clear that by having a large number of such surfaces, it will be possible to obtain full control of the system. At the same time, the realization of such a system is not simple. The main requirements that will guide the choice of the sling-load control system are 1) simplicity, 2) low cost, 3) reliability, 4) easy transportation, and 5) fast/easy installation on different kinds of external sling loads. These requirements lead to the conclusion that the number of control surfaces should be kept to a minimum and therefore those that remain should be most effective for their specific task.

All of the previous studies, dealing with sling-load instabilities, have indicated that the majority of instability problems involve lateral/directional motions. Therefore, it has been decided to use only two vertical surfaces, as shown in Fig. 2. One surface is located at the rear of the load and its main task is to apply yaw moments about the load center of mass. The other surface is located above the load center of mass and is responsible for exerting lateral forces that are not accompanied by directional moments. Both surfaces also exert rolling moments on the load.

The active control is obtained by changing the incidence angles of the surfaces, δ_I (rear surface) and δ_{II} (central surface). Thus, the two surfaces function as monoblock aerodynamic control surfaces. Since there is no directional preference the surfaces profiles are symmetric.

In order to obtain a simple flexible system, the two surfaces can be installed on a lightweight rigid frame that also carries the surfaces' actuators (electric actuators seem to be most appropriate) and some or all of the measurement devices. The frame can be attached to the load through the sling legs or by any other method that allows easy and quick assembly or disassembly.

The presence of the aerodynamic control surfaces affect the theoretical model in two major ways. First, the aerodynamic stability derivatives of the sling load are changed. Second, aerodynamic control derivatives are added. In order to introduce these two effects into the theoretical model, the aerodynamic forces and moments that are applied by the surfaces (on the load) should be calculated. These calculations are based on the following assumptions:

1) It is possible to obtain the aerodynamic coefficients of the external sling load with the aerodynamic surfaces by superposition of the coefficients of the load without the control surfaces and the control surfaces alone. In other words, it is assumed that mutual influences can be neglected.

2) The side-slip angle of the load is equal to zero at the trimmed flight condition.

3) The surfaces' incidence angles are zero at the trimmed flight condition.

4) Unsteady aerodynamic influences on the surfaces are not taken into account because of the relatively low frequencies of the system's motions, which are of interest here.

5) The surfaces are considered as finite wings. Thus, the surface's lift curve slope $C_{L\alpha}$ is given by (e.g., Ref. 16):

$$C_{L\alpha} \cong C_{l\alpha} \frac{\text{Æ}}{2 + \sqrt{4 + \text{Æ}^2}} \tag{6}$$

where $C_{l\alpha}$ is the two-dimensional lift curve slope of the profile, whereas Æ is the surface aspect ratio.

6) The influence of the spanwise component of the flow over the surface is neglected.

Based on the preceding assumptions, the aerodynamic forces that act on the surfaces are calculated. In these calculations, the surface center of pressure is taken as the representative point of the surface. Thus, the velocity of the incoming flow and the angle of attack are calculated at that point. The aerodynamic forces that act on each surface are calculated by

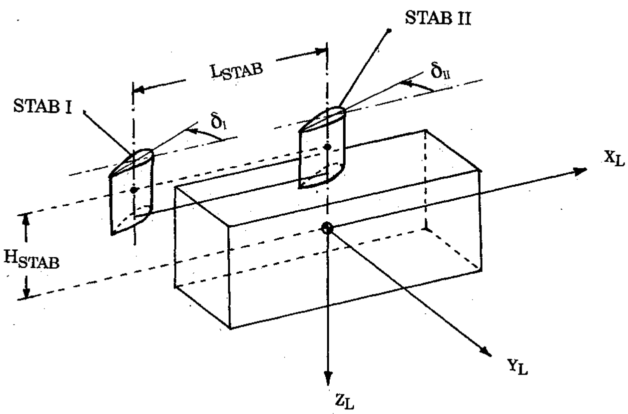

Fig. 2 The proposed load stabilization system (LSS).

using the well-known equations of the resultant lift and drag that act on finite wings. The lift curve slope is calculated by Eq. (6). The aerodynamic moments about the load center of mass are products of the aerodynamic forces and the appropriate components of the distance between each surface center of pressure and the load center of mass.

After calculating the contributions of the aerodynamic surfaces to the aerodynamic forces and moments, that act on the sling load, the calculation of their contributions to the aerodynamic stability derivatives and control derivatives is carried out. These contributions are added to the appropriate elements of the matrices $[A]$, $[B]$, and $[G]_L$.

As indicated previously, the terms of the matrices $[U_0]_L$ and $[U_1]_L$ represent the feedback gains of the control system. Since there are only two control variables associated with the load (δ_I and δ_{II}), $n_{\delta L}$ is equal to two. The specific control laws that define the matrices $[U_0]_L$ and $[U_1]_L$ are described in the next section.

Results and Discussion

A Sikorsky CH-53D helicopter with a gross weight of 15,5685 N (35,000 lb; not including the external sling load) will be considered in all of the examples of this paper. References 17 and 18 were used as sources for the data base of this helicopter. The helicopter's center of mass is located at its nominal location, as defined in Ref. 18.

The external sling load in all of the examples is a Military Standard Container, Milvan. The Milvan dimensions are 2.4 × 2.4 × 6.1-m (8 × 8 × 20-ft). The investigation will include different Milvan weights. For the present purposes, it is assumed that the Milvan mass moment of inertia components are given by

$$I_{ii} = (W_L / W_{L\text{ref}}) I_{ii\text{ref}} \tag{7}$$

where

$$ii \equiv xx, yy, zz. \qquad W_{L\text{ref}} = 4448 \text{ N} = 1000 \text{ lb}$$

$$I_{yy\text{ref}} = I_{zz\text{ref}} = 1623 \text{ kg-m}^2 = 1200 \text{ slug-ft}^2$$

$$I_{xx\text{ref}} = 411 \text{ kg-m}^2 = 303 \text{ slug-ft}^2$$

$$I_{xz} = 0$$

The available aerodynamic coefficients of the Milvan are presented in Ref. 4. This data is based on different experimental studies that have been reported previously. The data in Ref. 4 includes also quasisteady and unsteady aerodynamic influences. Unfortunately, the data associated with unsteady aerodynamics, applicable to the case of forward flight (which is the case of interest here), is very limited and insufficient.

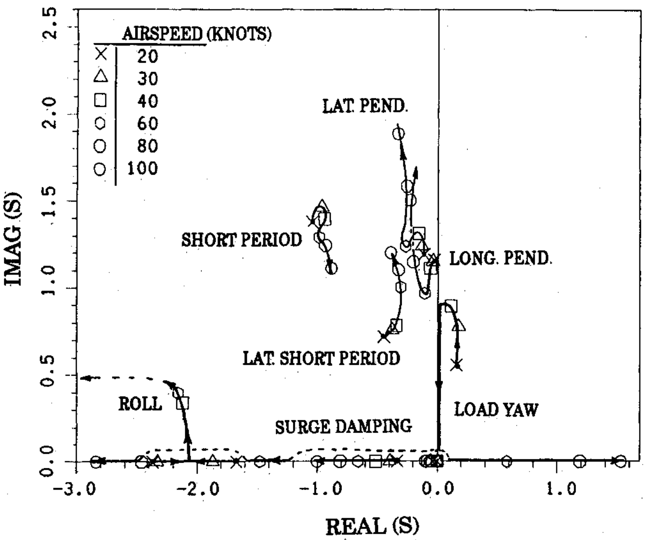

Fig. 3a Airspeed influence without LSS (weight ratio 0.1).

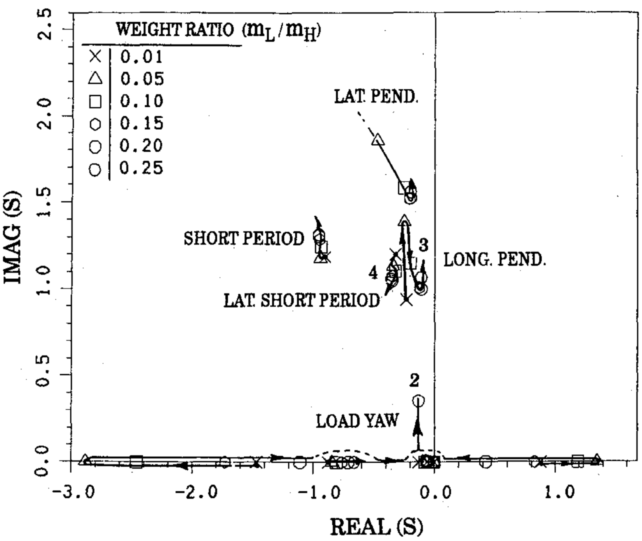

Fig. 3b Load weight influence without LSS (airspeed 80 knots).

Other sources also do not offer complete unsteady aerodynamic data, which is applicable to the present case. Limited studies reported in Ref. 15 have shown that, using the unsteady aerodynamic model and data that were presented in Ref. 4, the influence of unsteady aerodynamics on the stability at forward flight is very small and can be neglected from a practical point of view. The main influence of the unsteady aerodynamics includes the addition of new periodic roots (eigenvalues), which are stable and have relatively high frequencies. Still, since the model includes the detailed unsteady aerodynamics, it will be worthwhile to run cases again with a more complete unsteady aerodynamics data, when such data are available.

Since the present research deals with forward flight, where the wake lies almost horizontally behind the rotor, the wake influences on the external load aerodynamics are negligible.

The basic nominal sling legs geometry includes four legs that are attached to the upper four corners of the Milvan. The top of the sling legs is located at the point 0,0, − 7.62 m (0,0, − 25 ft)—relative to the load system of coordinates. In order to investigate the influence of the sling legs geometry on the system stability, cases of different heights of the sling legs system have also been considered.

Most of the examples that will be presented will not include an extension sling. In cases where such a sling is added, its length will be indicated. The elasticity of the extension sling in all of the cases is taken equal to 186,825 N · m/m (42,000 lb · in./in.).

If not stated otherwise, the nominal values that have been previously mentioned will be used. In all of the cases that will be considered, the basic trimmed flight condition involves a horizontal flight at a constant speed. Although the research[15] included investigations where the AFCS is inoperative, in all of the cases that will be presented in this paper, the more practical state of AFCS-ON is considered.

The initial steps of the investigation included a model validation, which is presented in Ref. 15.

In Fig. 3a, the roots of the helicopter/sling-load system are presented as a function of airspeed, when the load stabilization system (LSS) is not added yet. Only the roots that are important to the present investigation are shown. The unstable mode is denoted "load yaw." Although the load-yaw motion is the largest component of this mode, it also includes significant roll and side-slip motions. At low airspeeds this mode is unstable periodic, whereas at higher speeds the instability increases and the mode diverges exponentially. The other modes include:

1) Longitudinal and lateral pendulum motions of the load, coupled with other motions of the load and the helicopter;

2) Lateral short period, which is mainly characterized by yaw and side slip oscillations of the helicopter;

3) Short period, which is basically a longitudinal periodic motion;

4) Surge damping, which is mainly characterized by longitudinal motion of the helicopter;

5) Roll motion of the helicopter, which is heavily damped;

6) Modes associated with roots in the close vicinity of the origin, which represent the directional neutrality of the helicopter/sling-load system. In other words, the helicopter and load do not have any directional (azimuth) preference.

It is clear that in the present combination of a Sikorsky CH-53D and a Milvan, the unstable load-yaw mode, presents the problem that the LSS should cope with.

In Fig. 3b, the influence of the load weight on the system dynamics, at an airspeed of 80 knots, without an LSS, is presented. The instability of the load-yaw mode is increased when the weight ratio (m_L/m_H—ration between the load mass and helicopter mass) is increased in value from 0.01 to 0.05. Then, any increase of the load weight results in a decrease of the instability. At relatively high loads (weight ratios greater than 0.2), the mode becomes periodic stable (see 2 in Fig. 3b). Investigation of the eigenvectors themselves indicates (as physically expected) that as the weight ratio is increased, the coupling between the load motion and the helicopter motion is increased. An interesting phenomenon is related to the fact that the longitudinal pendulum mode and the lateral short-period mode become very close (3 and 4 in Fig. 3b). As a result, the two modes are highly coupled, very similar, and include both the longitudinal pendulum motion of the load and the helicopter yaw and side-slip motions. Thus, the importance of a fully coupled analysis is evident. More evidence on the importance and necessity of a fully coupled analysis is presented in Ref. 15. The interested reader may find in Ref. 15 additional interesting detailed studies on the basic helicopter/sling-load system dynamics (without LSS).

As indicated above, the LSS includes two vertical aerodynamic surfaces. As a first stage of studying the LSS effectiveness, the influence of fixed surfaces is investigated, namely, the incidence angles δ_I and δ_{II} are kept constant and equal to zero. In all of the examples that will be presented, the area of each surface is equal to 1.86 m^2 (20 ft^2) with an aspect ratio of 1.33. This area presents a feasible and practical design (in the case of a Milvan). In all of the cases, the surface locations (see Fig. 2) are defined by $L_{stab} = 4.57$ m (15 ft) and $H_{stab} = 2.13$ m (7 ft). In Ref. 15, studies on the influence of the surface area are presented.

In Fig. 4, the airspeed influence, in the case of fixed aerodynamic surfaces, is presented. Comparison between Fig.

4 and Fig. 3a indicates that the surfaces reduce the instability of the system (the unstable load-yaw roots are moving to the left). The influence increases with the airspeed, which results in increased aerodynamic loads. At an airspeed slightly higher than 40 knots, the load-yaw mode becomes stable (1a in Fig. 4). This mode remains stable and periodic (1b in Fig. 4) up to an airspeed of 70 knots, when it becomes exponential (yet stable at this airspeed). At an airspeed of 80 knots, the mode becomes unstable again (1c of Fig. 4), but its divergence rate is much smaller (half or less) compared with the case of a load that does not have fixed surfaces (Fig. 3a).

Further studies for different weight ratios and suspension system geometries[15] indicate that fixed surfaces reduce the system instability, but instability problems still exist.

The complete configuration of the LSS includes surfaces that change their incidence angles as a function of the control system commands. It is possible to consider a case where all of the possible feedback combinations are realized, namely, a case where all of the elements of the matrices $[U_0]_L$ and $[U_1]_L$ are nonzero. Such a design will be impractical since the number of measurements is very large. In an effort to simplify the LSS, and because the instability usually involves lateral/directional motions, only the reduced lateral directional case will be considered while determining the feedback system design. The lateral variables include lateral velocities (v_H,v_L), roll rates (p_H,p_L), yaw rates (r_H,r_L), roll angles (ϕ_H,ϕ_L), and yaw angles (ψ_H,ψ_{Ls}). Thus, one has to determine the 20 feedback gains between the above ten variables and the two control variables, δ_{I} and δ_{II}. This task belongs to the class of MIMO problems (multiple input, multiple output). In the present investigation, a tool from the optimal control theory is used. The choice of the gains is based on a minimization of a penalty function that includes a combination of changes in the state variables and the control variables, applying predetermined weighting between both. The controller in this case is denoted LQR (linear quadratic regulator). The interested reader may find more details in Ref. 19 or other textbooks on optimal control. The solution involves Riccati equations. There are different numerical methods of solving these equations; for example, see Ref. 20.

The optimal gains have been calculated for different combinations of airspeeds, weight ratios, and suspension geometries. It has been found that the optimal gains did not vary much from one combination of parameters to another. This fact indicates the low sensitivity of the optimal control system to changes in the different plant's parameters. This is a very favorable character when it comes to practical realization. In Table 1 the average gains (average between the different combinations) are presented. These gains will be used as a nominal basic choice of gains for further studies.

Since the gains, which are presented in Table 1, represent an average between different optimums of different combinations of parameters, and since they are based on a reduced lateral/directional model, there is a place to check the performance of the complete coupled system, while the gains of Table 1 are used. The results are presented in Fig. 5. It can be seen that the helicopter/sling-load system is stable throughout the entire airspeed range. As shown in this figure, the stability of the problematic load-yaw mode increases with airspeed. The stability of this mode deteriorates slightly only at very high airspeeds, but still remains highly stable.

The results in Table 1 indicate that the gains of the central aerodynamic surface (δ_{II}) are relatively small. This may indicate that the effectiveness of this surface is small. Different studies (comparing cases where this surface is included with cases where the surface is excluded, see Ref. 15) have confirmed this observation. Therefore, it has been decided to use only the rear aerodynamic surface in what follows.

Although the gains of Table 1 stabilize the system, the realization of such a system is still difficult. Practical measurement of many of the lateral directional variables is complicated, inaccurate, and expensive. Therefore, in order to arrive at an efficient LSS, a comprehensive parametric study has been carried out in order to find whether it is possible to use a smaller number of feedback loops. The guideline in this study was the need to arrive at a simple, inexpensive, and easy-to-realize LSS. The entire study is described in Ref. 15 and resulted in a recommended LSS.

The recommended LSS includes feedbacks that are based on the helicopter's and sling-load's roll and yaw rates (p_H,r_H,p_L,r_L). The helicopter rates may be easily obtained for the AFCS measurements, while the load rates can be mea-

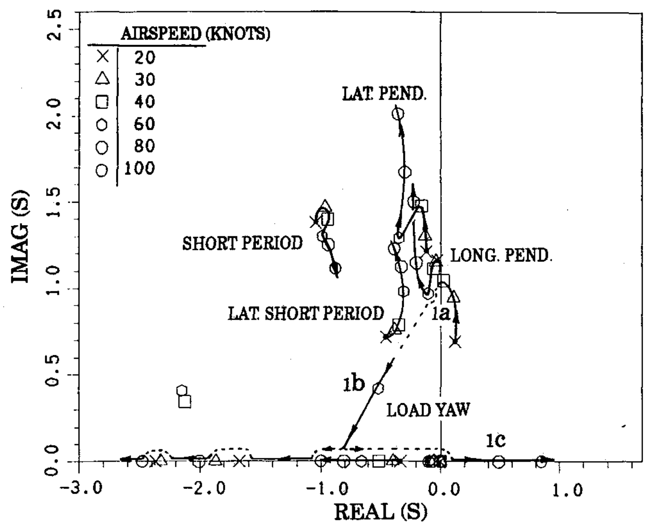

Fig. 4 Airspeed influence in the presence of fixed stabilization surfaces (weight ratio 0.1).

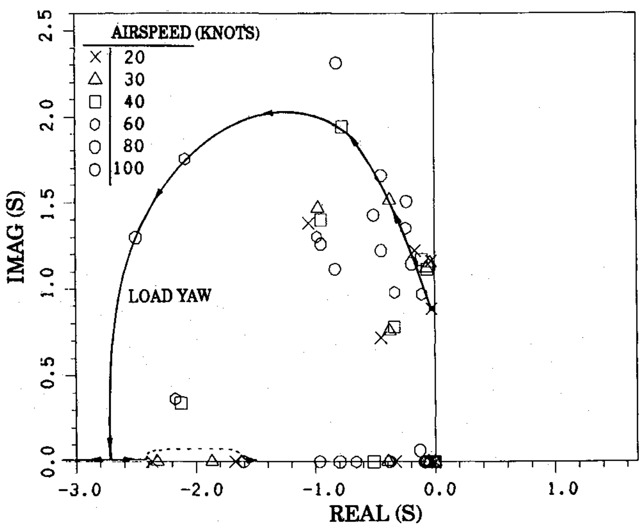

Fig. 5 Verification of an LSS that includes all the feedbacks of Table 1 (weight ratio 0.1).

Table 1 Nominal average gains

	δ_{I}, rad	δ_{II}, rad
v_H, ft/s	0.004	0.0005
v_L, ft/s	0.04	−0.001
p_H, rad/s	0.8	−0.1
r_H, rad/s	2.0	−0.4
p_L, rad/s	0.8	−0.2
r_L, rad/s	−2.0	0.05
ϕ_H, rad	2.0	−0.2
ψ_H, rad	1.6	−0.2
ϕ_L, rad	0.8	−0.1
ψ_L, rad	−0.4	0

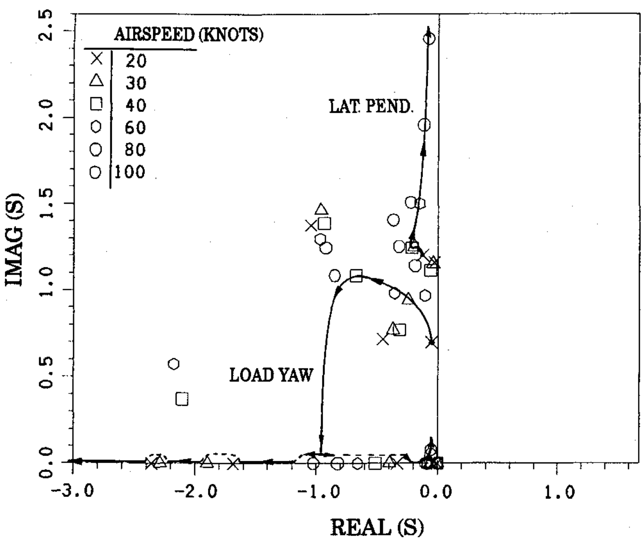

Fig. 6a Airspeed influence, while using helicopter and load angular rates (p_H, r_H, p_L, r_L) feedbacks (weight ratio 0.1).

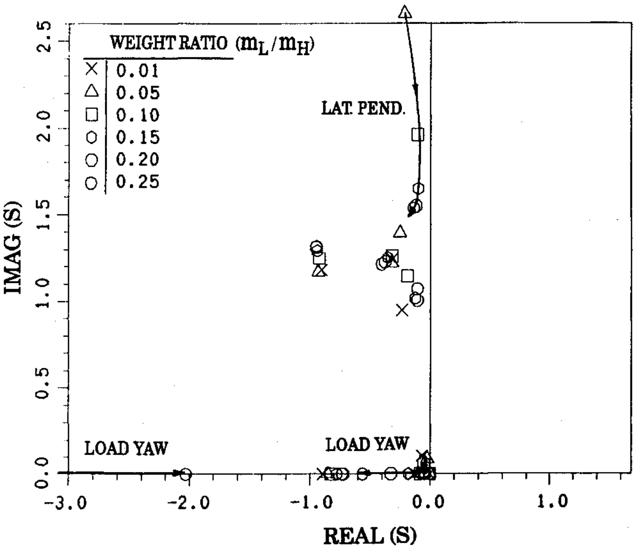

Fig. 6b Load weight influence, while using helicopter and load angular rates (p_H, r_H, p_L, r_L) feedbacks (airspeed 80 knots).

sured by installing a package of rate gyros on the load (which are relatively inexpensive, rugged, and reliable). The studies of Ref. 15 included different combinations of different gains. These studies have shown that the nominal gains, as presented in Table 1, offer good performance of the LSS in a very wide spectrum of parameters. Therefore, in all of the examples that will be presented, the nominal values are chosen.

In Fig. 6a, the roots of the system with the recommended LSS, as a function of airspeed, are described. It can be shown that the system is stable throughout the entire range, although the stability clearly deteriorates, compared to the case of using the measurements of all of the lateral state variables with the optimal gains (see Fig. 5). In Fig. 6b, the influence of the weight ratio at an airspeed of 80 knots is presented. Again, the system is stable in the entire range. Similar results have also been obtained at an airspeed of 100 knots.

Figures 6a and 6b present the relative insensitivity of the recommended LSS (which is based on helicopter and load angular rates) when it comes to variations in airspeed and in the load weight. Figures 7 and 8 show that this important property of low sensitivity to changes in the helicopter/sling-load system includes also other system parameters. In Fig. 7, the case of a standard sling-legs system with an elastic extension sling of 10 ft is shown. As expected, the frequency of the pendulum modes is reduced. As a result of this trend, the frequencies of a few different modes (lateral and longitudinal pendulums and lateral short period) become very close and the coupling of the modes increases significantly. Similar trends are obtained while increasing the sling-legs height.

Whereas, in all of the previous examples, changes in the geometric, inertia, or flight condition data have been considered. In Fig. 8, the influence of changes in the aerodynamic properties of the load is investigated. The aerodynamic-stability derivatives of the Milvan are varied relative to the nominal case, in a random manner, allowing up to $\pm 40\%$ changes. Comparison between Figs. 6a and 8 show that in general the behavior is similar, whereas there is some decrease in the stability of the lateral pendulum mode, which gets very close to the stability limit. Deterministic changes of the aerodynamic properties of the sling load have shown similar trends (see Ref. 15).

The results that have been presented so far, and other results that are presented in Ref. 15, indicate that the proposed LSS (based on p_H, p_L, r_H, r_L), which is practical and easy to realize, will be effective for a wide range of helicopter/sling-load combinations.

Examination of Figs. 5–8 may raise one point of concern. Although the yaw mode becomes stable, the stability of the

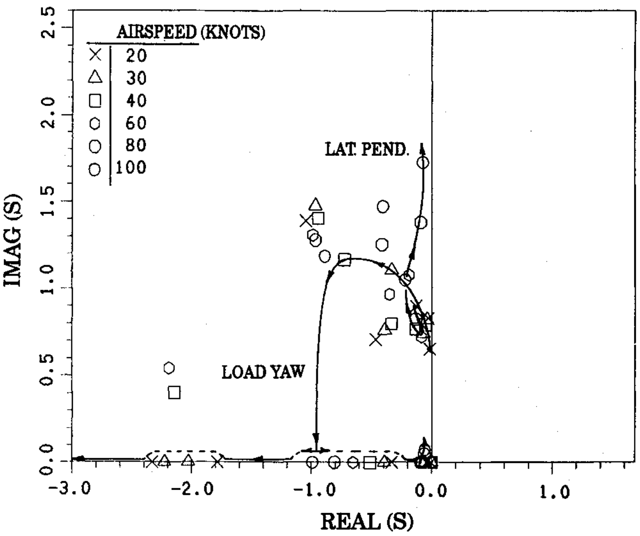

Fig. 7 Extension sling influence, while using helicopter and load angular rates (p_H, r_H, p_L, r_L) feedbacks, at different airspeeds (weight ratio 0.1, extension sling length 10 ft).

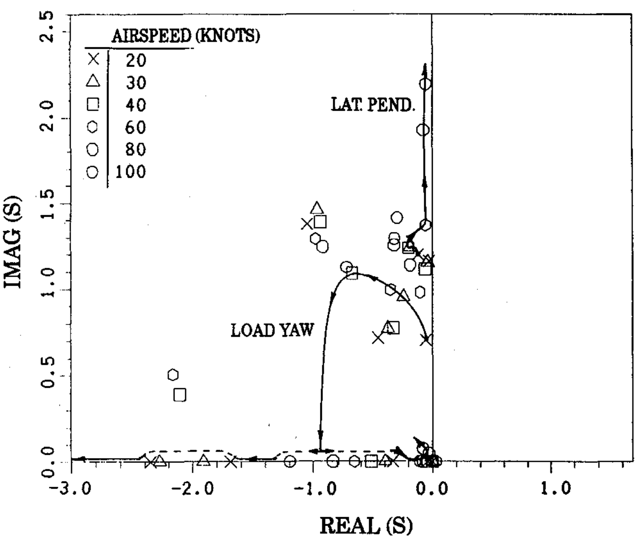

Fig. 8 Influence of random changes in the aerodynamic coefficients of the load, while using helicopter and load angular rates (p_H, r_H, p_L, r_L) feedbacks, at different airspeeds (weight ratio 0.1).

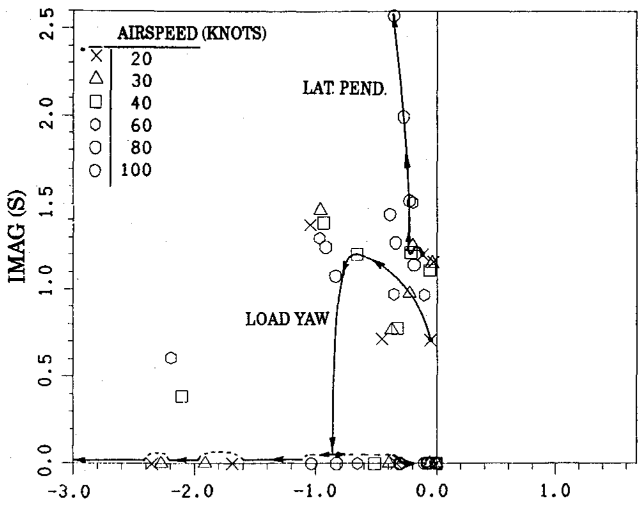

Fig. 9 Airspeed influence, while using helicopter and load angular rates (p_H,r_H,p_L,r_L) and load lateral acceleration a_{yL} feedbacks (weight ratio 0.1, lateral acceleration gain −0.02).

lateral pendulum mode deteriorates. At relatively high airspeeds, this mode approaches the stability limit (even so, studies have shown that the stability is not lost even at an airspeed of 150 knots). The possibility of increasing the stability of this mode by adding again the central surface has been investigated. Although certain increase in the stability has been observed, the improvement is very small and does not seem to be worth the additional complexity. Further studies have shown that a feedback based on the load lateral acceleration may be effective for that purpose. Since lateral acceleration is not one of the state variables, its optimal gain is not obtained in the usual optimal control approach. Parametric studies have led to a gain of −0.02, between the load lateral acceleration (in ft/s^2) and the incidence variation (in radians) of the rear aerodynamic surface. Results of adding this feedback to the recommended LSS (which is based on the helicopter and sling-load angular rates) are presented in Fig. 9. It can be seen that the stability of the lateral pendulum mode at high airspeeds is largely increased. This feedback seems to be appealing because of the relative ease of its realization (installing an unidirectional accelerometer on the load). Additional studies, which are reported in Ref. 15, indicate that the load lateral acceleration feedback increases the stability of the lateral pendulum mode over a wide range of helicopter/sling-load configurations.

The investigation of the influence of the LSS included also time-response studies (of the helicopter/sling-load system) to different disturbances (see Ref. 15). The trends were identical to what can be expected for the root-locus plots.

Conclusions

Examination of a CH-53D helicopter with a standard Milvan as a sling load, using a single suspension point, has let to the following conclusions:

1) The system dynamics include an unstable mode that is mainly characterized by a load yaw motion.

2) Installing fixed vertical aerodynamic surfaces on the sling load may reduce the instability, but instability still exists at high airspeeds (when practical sizes of surfaces are considered).

3) It is possible to stabilize the helicopter/sling-load system by using an active stabilization system, where the incidence angles of the vertical aerodynamic surfaces are controlled. The inputs to the control system are measurements of the lateral/directional state variables of the system.

4) An aerodynamic surface, which is located at the rear of the sling load, is very effective, while a surface located above the center of mass is ineffective and therefore should not be installed.

5) A system that is based on measuring the helicopter and sling-load angular rates is easy to realize and stabilizes the system in a wide range of airspeeds, weights, suspension configurations, and aerodynamic characteristics of the external sling load.

6) Adding to the above load-stabilization system, a feedback based on a measurement of the load lateral acceleration increases the stability of the lateral pendulum mode, which is otherwise on the verge of instability.

7) The studies have shown that it is important to use a general complete model of the helicopter/sling-load dynamics. At certain combinations of parameters, significant coupling between the longitudinal and lateral/directional motions are obtained. In many cases, strong coupling between the helicopter and sling-load motions is observed.

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