DYNAMIC STABILITY OF A HOSE-DROGUE-WING SYSTEM FOR AERIAL REFUELING

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Abstract: In this work the classical hose-drogue system has been modified by adding a small lifting surface at the end of the hose and just before the drogue. This small wing can help to stabilize the static position of the system as well as to improve the dynamic characteristic of the hose-drogue. The hose is assumed to behave like a cable with tension and no bending forces are considered at the present time. Assuming that the dynamic effects are small compared to the static effects, a linearized expression for the perturbed motion of the hose in the vertical plane and the incremental hose tension are obtained. The resulting equations are linear with variable coefficients that depend on the static equilibrium position and static tension of the hose. The wing at the end of the hose generates unsteady aerodynamic forces that depend on the vertical velocity of the hose at the end position and of the unsteady angle. These forces are taking into account by means of the simplified model of Theodorsen´s theory. The assumption of exponential dependence with time of the dynamic variables is made, and the resulting equations are solved by means of a finite element method. The system is thus transformed to an eigenvalue problem to obtain the natural frequencies and damping coefficients. The influence on the dynamic characteristics of the different parameters of the system is presented.

1. INTRODUCTION

Aerial refueling, also referred as air-to-air refueling (AAR) is the process of transferring fuel from one aircraft (the tanker) to another (the receiver) during flight. The procedure allows the receiving aircraft to remain airborne longer, extending its range or longer time on station. A series of air refueling can give range limited only by crew fatigue and engineering factors such as engine oil consumption. Because the receiver aircraft can be topped up with extra fuel in the air, air refueling can allow a take off with a greater payload which could be weapons, cargo or personnel: the maximum take-off weight is maintained by carrying less fuel and topping up once airborne. Alternatively a shorter take-off roll can be achieved because take off can be at a lighter weight before refueling once airborne. Aerial refueling has also been considered as a means to reduce fuel consumption on long distance flights greater than 3.000 nautical miles. Potential fuel savings with the range of 35-40% have been estimated for long haul flights [1].

The two main refueling systems are probe-and-drogue, which is simpler to adapt to existing aircraft, and the flying boom, which offers faster fuel transfer, but requires a dedicated operator station. Usually, the aircraft providing the fuel is specially designed for the task, although refueling pods can be fitted to existing aircraft designs if the probe-and-drogue system is to be used.

The entire process of an AAR operation with a hose-drogue-probe system could be divided into the following steps:

1. The tanker reaches a steady flight condition to perform the operation. Light-to-moderate turbulence conditions are required for a safe operation.

2. The tanker mission system operator (MSO) commands the hose-drogue system deployment. The hose is deployed at the extraction rate controlled by the control system that governs the motion of the extraction/retraction motor.

3. Once deployed, the hose-drogue system usually exhibits transient oscillations until it reaches a static equilibrium. The transient oscillations are induced by the motion of the AAR pods due to the tanker rigid body motion (flight mechanics) or the tanker wing flexible modes, the wing wake of the tanker, or the turbulence of the freestream.

4. Once the hose-drogue system stays in a position stable enough to perform the refueling, the receiver aircraft moves forward till its probe couples with the drogue.

For the steps 2 and 3 a linear theory for the steady and unsteady deformation of the hose can be considered [2]. For the step 4, the nonlinearity of the hose model is important [3-8]. During contact the force due to the probe on the drogue can make that the tension on the hose be reduced to a very low value or null. In that case the hose suffers of the whip phenomenon (see for example [8]) turning on jeopardy the operation and the integrity of both tanker and receiver aircrafts. When the hose has zones with low or zero tension together with high tension hybrid models like the shown in [7] have to be used. The case of low tension at the hose could also occur when the hose drum fails so even in the pre-contact phase the nonlinearity in the hose could be important for this special case.

At the pre-contact phase the stability of the hose-drogue system is important to assure the success of the contact. It has been stablished that a maximum amplitude of oscillation of the value of the drogue diameter is required to accomplish contact [9]. To avoid losses on the refueling process a control procedure to stabilize the drogue seems desirable. Several methods have been presented in the last decade to accomplish this [10-13]. One of the more promising seems to be the use of a small lifting surface to generate unsteady aerodynamics to assure the stable position of the drogue against external perturbations [10]. In the work of [10] the effect of a cruciform wing at the drogue position is investigated. The aerodynamic forces on the wing are considered after some measurements on a wind tunnel. If it is desired to implement an active control system of this type, a method to account for the unsteady aerodynamic forces generated should be considered. This paper includes a methodology for including unsteady forces associated to these small lifting surfaces.

The work presented in this paper considers a small wing in the horizontal plane and therefore analyzes the stability of the system in a vertical plane. The unsteady aerodynamic forces are evaluated using the strip theory. Since only the influence of the wing in the static equilibrium position and the influence in natural frequencies and damping coefficients are studied, these forces will be calculated in the frequency domain

The static equilibrium position of the hose-drogue system in the pre-contact phase is obtained and the influence of the small wing at the drogue position is assessed. For the configuration in equilibrium a dynamic analysis of the system are computed and the normal modes obtained. The work of Eichler [2] is thus generalized to include the effect of the wing at the end boundary condition. The hose is assumed unstreachable and no bending forces are considered at this time. Assuming that the dynamic effects are small compared to the static ones, a linearized expression for the displacement in the vertical plane and the dynamic component of the hose tension are obtained. The resulting equations are linear with variable coefficients that depend on the static equilibrium position and static tension of the hose. The wing at the end of the hose generates unsteady aerodynamic forces that depend on the vertical velocity of the hose end and of the unsteady angle. These forces are taking into account by means of a simplified strip theory and, for each strip, the lift is obtained by using the Theodorsen's theory [14]. The resulting equations, after assuming exponential dependence for the dynamic variables, are solved by means of a finite element method. The system is thus transformed to an eigenvalue problem to obtain the natural frequencies and damping coefficients. The influence on the dynamic characteristics of the different parameters of the system is investigated.

2. AEROELASTIC MODEL OF THE HOSE, DROGUE AND WING SYSTEM

The hose is assumed to stay on the *x-y* plane and no perturbations outside this plane are considered. If the hose is deployed along the plane of symmetry of the tanker this can be a good assumption but in the case that the hose is not on this plane the asymmetry of the vorticity shed by the wing will generate perturbations outside the x-y plane (see for example [10]) and this assumption will not hold anymore.

The hose is assumed to be under tension at all times and no bending forces nor axial deformation will be considered at the present study. If the hose-drum is operating and the receiver has not made contact with the drogue this hypothesis should hold. The equilibrium equations in the *x, y* plane are then

$$-\rho_H \frac{\partial^2 x}{\partial t^2} + q + T\frac{\partial^2 x}{\partial s^2} + \frac{\partial T}{\partial s}\frac{\partial x}{\partial s} = 0 \tag{1}$$

$$-\rho_H \frac{\partial^2 y}{\partial t^2} + p - \rho_H g + T\frac{\partial^2 y}{\partial s^2} + \frac{\partial T}{\partial s}\frac{\partial y}{\partial s} = 0 \tag{2}$$

where *(x,y)* denotes the position of the hose, s is the hose length, ρ_H is the mass of the hose per unit length, T is the tension of the hose, q the drag per unit length of the hose, and p is the lift per unit length.

Following Eichler [2] the following values will be used for p and q

$$q = \rho_\infty c_2 \left(\frac{d}{12}\right) U_\infty^2 \tag{3}$$

$$p = c_1 \sin^2 \alpha \tag{4}$$

Where ρ_∞ is the air density, $U_\infty$the freestream velocity, d the hose diameter, $c_1 = 0.57$ and $c_2 = 0.006$, and α is the local angle of attack of the hose.

The boundary conditions are,

$$\text{at } s = 0 \qquad x(0,t) = X_T(t); \qquad y(0,t) = Y_T(t) \tag{5}$$

where $X_T(t)$ and $Y_T(t)$ are the prescribed motion in the *x* and *y* direction of the hose contact point with the pod tanker aircraft.

At $s = s_0$, where s_0 is the hose total length, the boundary condition is expressed from the equilibrium of forces in the *x* and *y* directions as

$$-T\cos\alpha + Q = 0 \qquad \text{for small values of} \alpha,\ -T\frac{\partial x}{\partial s} + Q = 0 \tag{6}$$

$$T\sin\alpha + L + P - W - \frac{W}{g}\frac{\partial^2 y}{\partial t^2} = 0 \quad \text{for small values of } \alpha,\ \ -T\frac{\partial y}{\partial s} + L + P - W - \frac{W}{g}\frac{\partial^2 y}{\partial t^2} = 0 \tag{7}$$

where Q is the drogue resistance, P the drogue lift, *W* is the drogue weight (*W/g*, the drogue mass) and L the lift due to the wing placed at the end of the hose. This lift can be expressed as

$$L = \frac{1}{2}\rho_\infty U_\infty^2 S_a C_{L\alpha}\sin(\alpha_0 + \alpha(s_0,t)) \tag{8}$$

where S_a is the wing surface, $C_{L\alpha}$ the lift curve slope, α_0 the steady angle of attack measured respect to the zero lift line and $\alpha(s_0,t)$ the unsteady lift angle due to the motion of the hose at s_0. The flight condition is defined in terms of the air density ρ_∞ and flight speed U_∞.

If it is assumed that the hose is initially in static equilibrium and, due to external excitation like the tanker oscillation, wind turbulence or the wake of the wing, the steady state is perturbed with small amplitude, the variables $y(s,t)$, $x(s,t)$ and $T(s,t)$ can be expressed as

$$y(s,t) \cong y_e(s) + \delta_0\eta(s,t) \tag{9a}$$

$$x(s,t) \cong x_e(s) + \delta_0\xi(s,t) \tag{9b}$$

$$T(s,t) \cong T_e(s) + \delta_0\tau(s,t) \tag{9c}$$

where $y_e(s)$, $x_e(s)$ are the static equilibrium position for the hose-drogue-wing system, $T_e(s)$ is the static value of the tension along the hose, δ_0 is the small amplitude of the unsteady motion due to the disturbances, and $\eta(s,t)$, $\xi(s,t)$ and $\tau(s,t)$ are the perturbed values of the hose position and hose tension. Also, the lift on the wing can now be expressed as $L = L_0 + \delta_0 L_1$ where L_0 is the lift due to the static position of the wing and L_1 is the unsteady lift due to the plunging and pitching oscillation of the wing. It will be assumed that the wing is rigid and therefore there is no bending or torsion deformation.

Substitution of equations (9a), (9b) and (9c) into equations (1) and (2) and separating the stationary terms from the unsteady terms, results in the formulation detailed in the next sections.

3. STATIC EQUILIBRIUM FOR THE HOSE-DROGUE-WING SYSTEM

The governing equations for $x_e(s)$, $y_e(s)$ and $T_e(s)$ are

$$q_0 + \frac{d}{ds}\left(T_e \frac{dx_e}{ds}\right) = 0 \tag{10}$$

$$p - \rho_H g + \frac{d}{ds}\left(T_e \frac{dy_e}{ds}\right) = 0 \tag{11}$$

With the boundary conditions

$$\text{at } s = 0 \qquad x_e(0) = 0, \qquad y_e(0) = 0 \tag{12a}$$

$$\text{at } s = s_0 \qquad T_e \frac{dx_e}{ds} = Q_0 \quad -T_e \frac{dy_e}{ds} + L_0 + P - W = 0 \tag{12b}$$

For small values of the angle of attack of the wing $L_0 = \frac{1}{2}\rho_\infty U_\infty^2 S_a C_{L\alpha}\left(\alpha_0 - \frac{dy_e}{ds}\right)$.

Equations (10) and (11) can be integrated to give the steady position of the hose-drogue-wing system. To do so a compatibility condition is needed requiring that $ds^2 = dx_e^2 + dy_e^2$.

Performing a first integration on equation (11) the following results is obtained

$$\frac{dy_e}{ds} = -\frac{q_0}{2\Phi} + \frac{\sqrt{\nu}}{2\Phi}\left(\frac{f(s)+1}{f(s)-1}\right) \tag{13}$$

Where

$$\Phi = \rho_H g \frac{3}{2} + c_1 \tag{14a}$$

$$\nu = q_0^2 + 4\rho_H g \Phi \tag{14b}$$

$$f(s) = \left(\frac{2\Phi z_0 + q_0 + \sqrt{\nu}}{2\Phi z_0 + q_0 - \sqrt{\nu}}\right)\left(\frac{Q + q_0(s - s_0)}{Q}\right)^{\frac{\sqrt{\nu}}{q_0}} \tag{14c}$$

$$z_0 = \frac{W - L_0}{Q + L_{0\alpha}} \tag{14d}$$

$$L_{0\alpha} = \frac{1}{2}\rho_\infty U_\infty^2 S_a C_{L\alpha} \tag{14e}$$

Where P it has been assumed that is very small compared to the drogue weight W and to the wing lift L_0 and therefore it has been neglected at equation (12b).

The value of $\frac{dx_e}{ds}$ can be obtained from the compatibility condition as

$$\frac{dx_e}{ds} = \left[1 - \left(-\frac{q_0}{2\Phi} + \frac{\sqrt{\nu}}{2\Phi}\left(\frac{f(s)+1}{f(s)-1}\right)\right)^2\right]^{1/2} \tag{15}$$

And the tension along the hose as

$$T_e(s) = \frac{q_0(s_0 - s) + Q}{\frac{dx_e}{ds}} \tag{16}$$

Equations (13) and (15) are integrated numerically together with the boundary conditions at $s=0$ to obtain the position of static equilibrium for the hose.

By substitution of equation (15) at (16) the tension along the hose is obtained without the need of any more integration.

4. DYNAMIC FORMULATION FOR THE HOSE-DROGUE-WING SYSTEM

The terms of order δ_0 provide the equations for the dynamic motion of the hose. These equations are:

$$-\rho_H \frac{\partial^2 \xi(s,t)}{\partial t^2} + \frac{\partial}{\partial s}\left[T_e(s)\frac{\partial \xi(s,t)}{\partial s} + \tau(s,t)\frac{dx_e(s)}{ds}\right] = 0 \tag{17}$$

$$-\rho_H \frac{\partial^2 \eta(s,t)}{\partial t^2} - \frac{dp}{d\alpha}\bigg|_{\alpha_0}\left(\frac{\partial \eta(s,t)}{\partial s} + \frac{1}{U_\infty}\frac{\partial \eta(s,t)}{\partial t} - \frac{w_G}{U_\infty}\right) + \frac{\partial}{\partial s}\left[T_e(s)\frac{\partial \eta(s,t)}{\partial s} + \tau(s,t)\frac{dy_e}{ds}\right] = 0 \tag{18}$$

Where w_G is the vertical component of the fluctuating freestream velocity.

The boundary conditions for the dynamic problem are

$$\text{At} \quad s = 0 \quad \xi(0,t) = X_T(t) \qquad \eta(0,t) = Y_T(t) \tag{19a}$$

$$\text{At} \quad s = s_0 \quad T_e(s)\frac{\partial \xi(s,t)}{\partial s} + \tau(s,t)\frac{dx_e}{ds} = 0; \qquad -T_e(s)\frac{\partial \eta}{\partial s} - \tau(s,t)\frac{dy_e}{ds} + L_1 - \frac{W}{g}\frac{\partial^2 \eta}{\partial t^2} = 0 \tag{19b}$$

Where L_1 is the unsteady lift on the wing. As a first approximation this lift can be evaluated like if the wing be of infinity aspect ratio. Using the result of Theodorsen [14] this lift can be expressed as

$$L_1(s_0,t) = \pi\rho_\infty S_a\left\{\frac{b}{2}\left[-\frac{\partial^2 \eta}{\partial t^2} + U_\infty\frac{\partial^2 \eta}{\partial s \partial t} - ba\frac{\partial^3 \eta}{\partial s \partial t^2}\right] + \right.$$
$$\left. + C(k)U_\infty\left[-\frac{\partial \eta}{\partial t} + U_\infty\frac{\partial \eta}{\partial s} + b\left(\frac{1}{2} - a\right)\frac{\partial^2 \eta}{\partial s \partial t^2}\right]\right\} \tag{20}$$

Where *C(k)* is the Theodorsen´s function.

These equations can be solved adding the compatibility condition for the unstretched hose that is

$$\frac{dx_e}{ds}\frac{\partial \xi}{\partial s} + \frac{dy_e}{ds}\frac{\partial \eta}{\partial s} = 0 \tag{21}$$

Having so three equations (17), (18) and (21) to solve for the three unknowns $\xi(s,t)$, $\eta(s,t)$ and $\tau(s,t)$.

Following [2] it will be assumed that the tension at the hose does not change much during the hose oscillation and therefore the value of the incremental hose tension τ can be neglected approximated by cero. Now equations (17) and (18) are decoupled and can be solved separately.

The forced excitation of the system due to the pod oscillation or the gust can be solved by modal decomposition of the system. Thus, once the dynamic properties of the hose-drogue-wing are known it can be evaluated how the frequencies of excitation will affect to the hose. Also, it can be determined how the different parameters of the system, like altitude of flight, flight velocity, hose length, mass per unit length of the hose and wing area affect the natural frequencies and damping coefficient of the system.

Since the equations are decoupled first it will be solved for the y component of the perturbation disturbance. Thus, by letting $\eta(s,t) = N(s)e^{i\omega t}$ and after substitution in equation (18), the following equation and boundary condition are obtained for *N(s)*

$$\rho_H \omega^2 N(s) - \frac{dp}{d\alpha}\bigg|_{\alpha_0}\left(\frac{dN(s)}{ds} + i\frac{\omega}{U_\infty}N(s)\right) + \frac{d}{ds}\left[T_e(s)\frac{dN(s)}{ds}\right] = 0 \qquad (22)$$

And the boundary conditions

$$\text{at} \qquad s = 0 \quad N(0) = 0 \qquad (23a)$$

$$\text{at } s = s_0 \; - T_e\frac{dN}{ds} + \pi\rho_\infty S_a\left\{\frac{b}{2}\left[-\omega^2 N(s) + (i\omega U_\infty + ba\omega^2)\frac{dN}{ds}\right] + C(k)U_\infty\left[-i\omega N(s) + \left(U_\infty + b\left(\frac{1}{2} - a\right)i\omega\right)\frac{dN}{ds}\right]\right\} + \frac{W}{g}\omega^2 N(s) = 0 \qquad (23b)$$

Also $\xi(s,t)$ can be expressed as $\xi(s,t) = X(s)e^{i\omega t}$ and the value of $X(s)$ can be obtained from equation (21) as

$$\frac{dX(s)}{ds} = -\frac{dN(s)}{ds}\frac{dy_e/ds}{dx_e/ds} \qquad (24)$$

This equation can be integrated with the boundary condition at $s = 0$ $X(0) = 0$

5. FINITE ELEMENT SOLUTION

Letting $\lambda = i\omega$ equation (22) can be expressed as

$$-\lambda^2 A(s) + \lambda B(s) + C(s) = 0 \qquad (25)$$

Where

$$A(s) = \rho_H N(s)$$

$$B(s) = -\frac{dp}{d\alpha}\bigg|_{\alpha_0}\frac{1}{U_\infty}N(s)$$

$$C(s) = T_e(s)\frac{d^2N}{ds^2} + \left(\frac{dT_e}{ds} - \frac{dp}{d\alpha}\bigg|_{\alpha_0}\right)\frac{dN}{ds}$$

$$\text{And } \frac{dp}{d\alpha}\bigg|_{\alpha_0} = -2c_1\frac{dy_e}{ds}$$

Together with the boundary conditions

$$s = 0 \quad N(0) = 0 \qquad (26a)$$

$$s = s_0 \quad \lambda^2 a_e(s) + \lambda b_e(s) + c_e(s) = 0 \qquad (26b)$$

Where

$$a_e(s) = \pi\rho_\infty S_a\frac{b}{2}(-ba)\frac{dN}{ds} - \frac{W}{g}N(s) - \pi\rho_\infty S_a\frac{b}{2}N(s)$$

$$b_e(s) = \pi\rho_\infty S_a\left[\frac{b}{2}U_\infty\frac{dN}{ds} - \frac{b}{2}N(s) + C(k)\left\{U_\infty b\left(\frac{1}{2} - a\right)\frac{dN}{ds} - U_\infty N\right\}\right]$$

$$c_e(s) = T_e(s)\frac{dN}{ds} + \pi\rho_\infty S_a C(k)U_\infty^2\frac{dN}{ds}$$

Equations (25) and (26) are solved by applying a finite element procedure. The hose is divided into J_L elements and on each element a linear approximation to *N(s)* is taken. Letting y_j the vertical displacements at the nodes the formulation of the finite element will result in the homogeneous system of equations

$$(\lambda^2[M_h] + \lambda[F_h] + [K_h])\{y_j\} = \{0\} \quad (27)$$

Where $[M_h]$, $[F_h]$ and $[K_h]$ represent equivalent mass, damping and rigidity matrices of the system. Solution of the eigenvalues of the above system of equations $\lambda_r = \sigma_r + i\omega_r$ gives the damping and natural frequencies of the hose-drogue-wing system, the eigenvectors will be the modes of vibration of the hose.

It should be noted that for the computation of the eigenvalues the unsteady lift force at $s = s_0$ depend on the frequency of oscillation. Thus an iteration procedure has to be developed to obtain the eigenvalues. First a value of the reduced frequency k is assumed, so the Theodorsen function *C(k)* can be evaluated, next the eigenvalues of the system are computed. If the natural frequency of some eigenvalue is equal to the value assumed for the evaluation of the reduced frequency k, that would be the solution; if not, a corrected value for k should be used and the procedure repeated. Usually two or three iterations are enough to reach a converged solution. However, with this procedure the natural frequencies and damping coefficients of the system have to be computed one at each time. When there is no wing, case $S_a=0$, all the eigenvalues can be computed at once.

6. RESULTS FOR THE STATIC EQUILIBRIUM POSITION OF THE HOSE-DROGUE-WING SYSTEM

Next equations (13), (15) and (16) are solved for a hose with the following properties, hose length of 15.24 m, hose mass per unit length of 2.765 kg/m and a hose diameter of 0.00508 m. Three flight conditions are considered, the first one, (case #1), is at sea level, with an air density of 1.225 kg/m^3 and a flight speed of 102.8 m/s, the second one, (case #2), for an altitude of 10.000 ft., air density of 0.9046625 kg/m^3 and a flight speed of 102.8 m/s, and for the third one (case #3) the altitude is of 25.000 feet, the air density of 0.5489225 kg/m^3 and the flight speed of 105.37 m/s. The drogue has a weight of 234.71 N.

In figure 1 the influence of the wing on the static position of equilibrium is analyzed for the three flight conditions. The wing has an aspect ratio of 3.5, a span of 0.7 m and a chord of 0.2 m giving a reference surface area S_a of 0.14 m^2. In the figure it can be observed that the effect of the wing is to reduce by a value of about 40% the drop of the drogue. Although an aerodynamic correction on the wing to account for the three dimensional effects should be applied, still it can be concluded that the influence of the wing is notable.

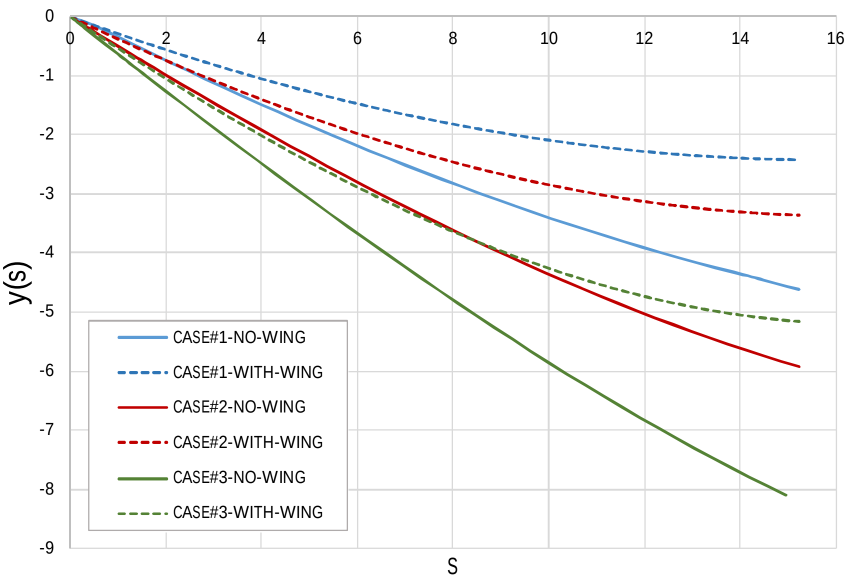

Figure 1. Influence of the wing on the static hose position for different flight conditions.

In figure 2 the influence of the aspect ratio of the wing is evaluated for the case #1. The wing span is kept constant to the value of 0.7m. It can be observed that small area of the wing, *AR*=7, *Sa*=0.07 m^2 already rise the drogue by a large amount from the value of -4.5 m to -2.75 m. Increasing the wing area does not affect much to the static stable position rising the drogue from -2.75 m to -2.375 m with an increase of more than twice the wing area.

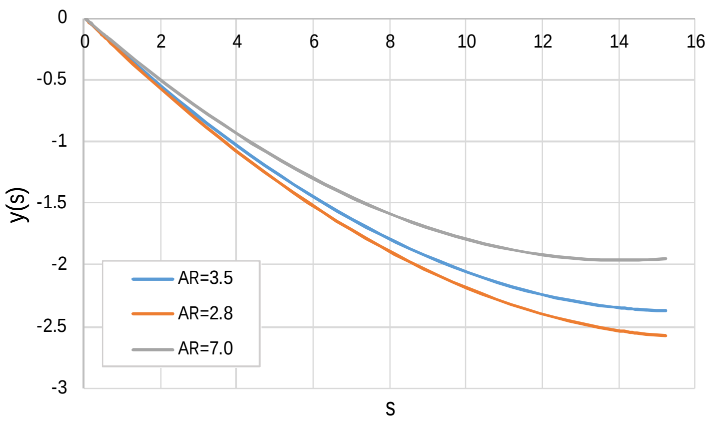

Figure 2. Effect of the wing aspect ratio on the static hose position for a fixed flight condition.

In figure 3 the hose tension along the hose length is represented for the case #1 with and without wing. The wing used for this case is one with an aspect ratio of 3.5, span 0.7 m and a chord of 0.2 m. In the figure it can be observed that the wing reduces the tension by a value of about a 5% at the hose drum and less than 2% at the hose end. When waves are generated along the hose this effect can be important.

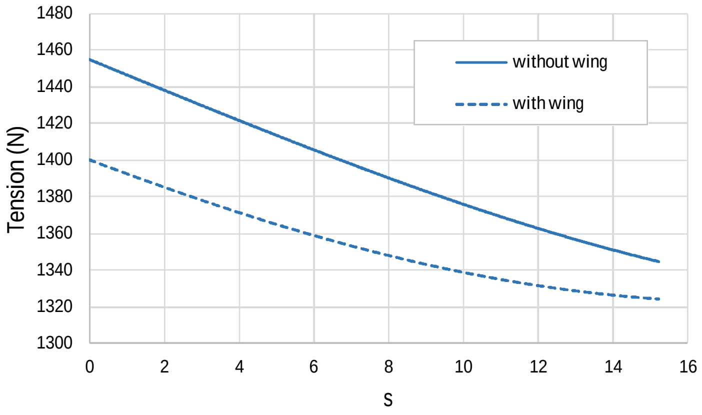

Figure 3. Influence of the wing on the static tension distribution on the hose for a fixed flight condition.

In figure 4 the effect of the wing chord and of the wing span on the hose tension is investigated for the case #1. In the figures it can be observed that while the tension at the drogue does not change with the aspect ratio of the wing and also with the wing area at the hose-drum there is a variation of about a 5%.

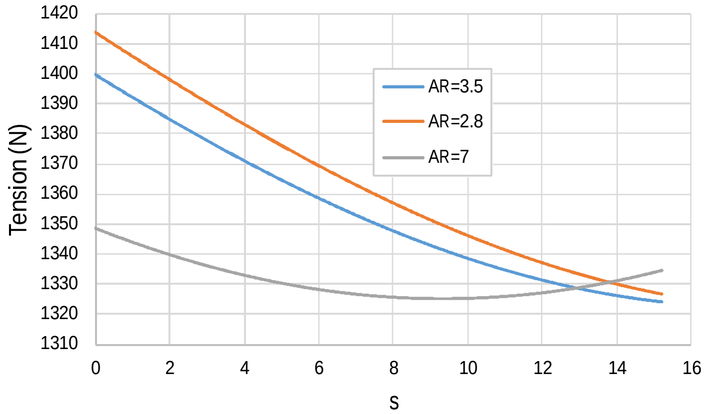

Figure 4. Effect of the wing aspect ratio on the static tension distribution on the hose.

It can be concluded then that the effect of the wing is to produce an important change on the hose static equilibrium position but not on the tension. Also that a wing with a small surface area is already enough to rise the drogue in a large quantity, so from the static equilibrium position a small wing can be enough to keep the drogue to the desired level.

7. RESULTS FOR THE DYNAMICS OF THE HOSE-DROGUE-WING SYSTEM

The non-dimensional damping coefficient and the natural frequencies for the system without and with the wing are computed for four different flight conditions. The results are presented in tables 1 and 2 respectively. For all the cases the damping of the hose has been ignored so the damping coefficient is due only the aerodynamic forces. In Table 1, without wing, it can be observed that the first frequency is less than one Hertz for all the flight conditions, this result is consistent with other computations presented for similar systems.

Therefore small oscillations of the tanker or the wing wake, both excitations occurring at low frequencies, can make the system to be highly amplified. The damping coefficient due to the aerodynamic lift on the hose is stable but with a very low value (less than 1% for all the modes and all the flight conditions).

Cases 1, 2 and 3 compare almost the same flight speed but different altitude. It can be observed that by increasing altitude the natural frequencies decrease, while the aerodynamic damping stays almost constant. Cases 3 and 4 are for the same altitude but increasing the flight speed, now the frequencies increases with the flight speed but the aerodynamic damping decreases.

	Alt 0 [ft] U∞=102.8 m/s		Alt 10000 [ft] U∞=102.8 m/s		Alt 25000 [ft] U∞=105.37 m/s		Alt 25000 [ft] U∞=177.84 m/s	
MODE NUMBER	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)
1	-0.00434	0.74476	-0.00464	0.65760	-0.00435	0.55074	-0.00205	0.84498
2	-0.00216	1.48989	-0.00231	1.31490	-0.00217	1.10063	-0.00102	1.69119
3	-0.00144	2.23493	-0.00154	1.97226	-0.00144	1.65069	-0.00067	2.53713
4	-0.00108	2.97993	-0.00116	2.62962	-0.00108	2.20079	-0.00050	3.38298
5	-0.00087	3.72490	-0.00093	3.28696	-0.00086	2.75086	-0.00040	4.22878

Table 1. Damping coefficient and natural frequencies for the hose-drogue system for different flight conditions.

In Table 2 the influence of the wing on the damping coefficient and natural frequencies is investigated for the same flight conditions. It can be observed that in all the cases the wing increase the damping coefficient by a value of about a 20%. Although the damping value still is very small this results show that the wing can help to improve the stability of the system. With regard to the natural frequencies these are almost non affected by the presence of the wing having values almost equal to the cases when there was no wing.

	Alt 0 [ft] U∞=102.8 m/s		Alt 10000 [ft] U∞=102.8 m/s		Alt 25000 [ft] U∞=105.37 m/s		Alt 25000 [ft] U∞=177.84 m/s	
MODE NUMBER	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)	DAMPING COEF.	FREQ. (Hz)
1	-0.00517	0.75965	-0.00516	0.67168	-0.00459	0.56328	-0.00281	0.86051
2	-0.00258	1.51718	-0.00258	1.34148	-0.00230	1.12500	-0.00140	1.71860
3	-0.00172	2.27488	-0.00172	2.01140	-0.00153	1.68677	-0.00093	2.57690
4	-0.00129	3.03215	-0.00129	2.68089	-0.00115	2.24812	-0.00070	3.43477
5	-0.00103	3.78845	-0.00103	3.34940	-0.00091	2.80850	-0.00056	4.29167

Table 2. Damping coefficient and natural frequencies for the hose-drogue-wing system for different flight conditions.

From these results it can be concluded that a small wing can be used as a way to stabilize the hose-drogue system either in a passive way as shown in this paper or in an active way when the value of the tension on the hose is not null. For an active control of the system the aerodynamic forces on the wing should be evaluated in the Laplace domain [15] and the drogue can be sustained at a stable position when contact with the receiver is about to occur.

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