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Flight Dynamics Simulation of a Heavy Lift Airship

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Performance, stability, and control characteristics of a quad-rotor heavy lift airship concept with a simply suspended payload are determined by using an analytical model of such a configuration. Nonlinear equations of motion have been used to construct a hybrid computer simulation of the system as well as to derive a linear system model of the configuration dynamics. Results are presented that show 1) the performance of the vehicle in typical missions, such as offloading container ships and logging; 2) possible instabilities of the configuration dynamics; and 3) controllability of the vehicle-payload system in the flight envelope of operational interest.

Nomenclature

B	= force due to vehicle buoyancy, lb
g	= acceleration due to gravity, ft/s^2
I	= moment or product of inertia of the vehicle, slug-ft^2
K	= payload aerodynamic drag constant
l	= length of the payload suspension cable, ft
L	= rolling moment, ft-lb
m	= mass, slugs
M	= pitching moment, ft-lb
N	= yawing moment, ft-lb
p	= roll velocity of the vehicle, rad/s
q	= pitch velocity of the vehicle, rad/s
r	= yaw velocity of the vehicle, rad/s
u	= longitudinal component of translational velocity in the x-direction of reference body axes, ft/s
v	= lateral component of translational velocity in the y-direction of reference body axes, ft/s
V_l	= absolute velocity of the payload, ft/s
w	= vertical component of translational velocity in the z-direction of reference body axes, ft/s
x,y,z	= coordinates of a point in the reference body axes system, ft
X,Y,Z	= components of external force along the x,y, and z axes, respectively, of the reference body axis system, lb
Δ	= prefix used for small perturbation
θ	= pitch attitude of the vehicle, rad
ϕ	= roll attitude of the vehicle, rad
ψ	= yaw attitude of the vehicle, rad

Subscripts and Superscripts

$(\dot{\ })$	= derivative with respect to time
$(\ )a$	= aerodynamic
$(\ )b$	= center of buoyancy
$(\ )c$	= center of mass
$(\ )^c$	= control
$(\ )e$	= equilibrium or trim value
$(\ )l,L$	= payload
$(\ )s$	= suspension point
$(\ )v$	= vehicle
$(\ )xx, xy$	= moment and product of inertia, respectively, about reference body axes system

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Introduction

RECENTLY there has been a growing need[1,2] for transporting large and heavy cargo that cannot be handled by conventional aircraft. Consequently, a new generation of vertical takeoff and landing vehicle concepts, particularly rotorcraft with unprecedented lifting capability, is being developed to airlift payloads externally on a sling. The heavy lift airship (HLA) concept belongs to this class of aircraft and offers the possibility of greatly improved low-speed controllability and station-keeping characteristics far beyond that of historical lighter-than-air (LTA) vehicles. This concept is now being considered for various civil and military applications, where externally suspended payloads are transported over short distances such as in offloading container ships, logging, or moving construction equipment.

Basically, the HLA consists of a rigid or nonrigid, buoyant, and nonrotating hull that is rigidly attached to a structural frame supporting the propulsion components. The advantage of such an arrangement is that the empty weight of the vehicle is supported by the force due to buoyancy while the propulsive forces are entirely available for lifting the payload and controlling the vehicle. Goodyear Aerospace has recently been involved in refining the HLA concept. The performance and control characteristics of various vehicle configurations have been studied with and without empennage and with propulsion components, such as gimballed helicopters—dedicated rotor systems, in combination with and without propellers for forward thrusting. As a result of such a study, an HLA configuration (Fig. 1) consisting of a buoyant hull with an empennage and four interchangeable rotor modules, each consisting of a lifting rotor and an auxiliary propeller, has been selected for development. To utilize fully the potential of this concept and also ensure that the vehicle-payload motion in the operational flight regime is stable and

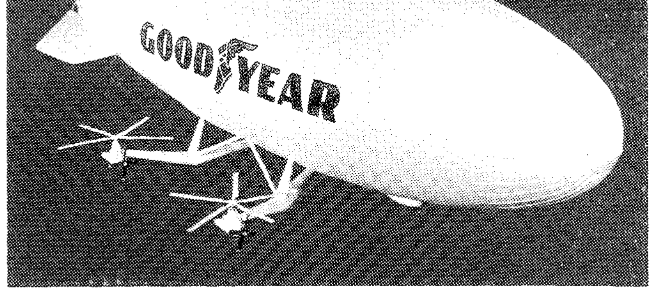

Fig. 1 Heavy lift airship configuration.

safe, Goodyear has been investigating the flight mechanics and control of such an HLA configuration. In this paper, the performance, stability, and control characteristics typical of this configuration are examined.

A mathematical model describing the motion of the HLA carrying a suspended payload has been derived by considering a simple model of such a configuration. The mathematical model is used to construct a hybrid computer simulation of the vehicle motion in a vertical plane to simulate typical missions of operational interest. To examine the stability of the HLA-payload motion in hover and forward flight, the nonlinear equations of motion were linearized about corresponding trim conditions to obtain a linear system model of the configuration dynamics. Subsequently, the controllability of the vehicle in the operational flight regime is investigated by considering typical control concepts.

Equations of Motion

Equations of motion of the HLA carrying a simply suspended payload are derived[3] by considering a simple model of such a configuration. The hull is assumed to be a buoyant, rigid body from which a payload, modeled here as a point mass, is suspended from an arbitrary point on the vehicle by means of a rigid, nonextensible link. The rotor modules in the configuration are assumed to be rigidly connected to the hard structure and are implicit devices that produce forces and moments on the vehicle for a specified flight path of the HLA and appropriate control inputs. Translation of the vehicle is described in terms of its velocity components u, v, and w along the x,y, and z axes, respectively, of a body axes system whose origin is located at an arbitrary point, while the rotational motion of the vehicle is described by the angular velocity components p, q, and r about the x,y, and z axes, respectively, of the same reference frame. The orientation of the vehicle is described by the Euler angles ϕ, θ, and ψ, which locate the body axes reference frame with respect to a local horizon system. Motion of the payload relative to the vehicle is described in terms of its coordinates x_L and y_L, which are defined in the reference body axes system of the vehicle. Note that only two independent coordinates are required to describe the payload motion, since it is assumed here that the payload remains at a constant distance equal to the cable length from the suspension point.

The dynamic equations of the combined HLA-payload system have been derived[3] by writing the equations of motion separately for the vehicle and the payload and then eliminating the unknown tension in the cable in these equations. In deriving the equations of motion of each body, the external forces and moments that are considered to be acting on the vehicle are due to gravity, buoyancy, aerodynamics of the hull, tension in the cable, and control inputs. Those on the payload are considered to be due to gravity and payload aerodynamic drag and a force equal and opposite to tension in the cable. The resulting equations are nonlinear and are coupled in the motion variables of the vehicle and payload.

HLA Flight Path Simulation

On the basis of the preceding mathematical model of the HLA, a hybrid computer simulation scheme has been set up to determine the operating time and fuel consumption characteristics of the HLA in typical missions. In this simulation model, aerodynamics of the vehicle are represented by equivalent lift and drag forces acting on the hull. For a given flight condition and control input, the thrust developed by each of the rotors is determined by considering the corresponding hp requirement. Forward motion of the vehicle is controlled by the longitudinal cyclic pitch on all the lifting rotors and the collective pitch on the auxiliary propellers; vertical motion of the vehicle is controlled by the collective pitch input in unison with all the lifting rotors. Two

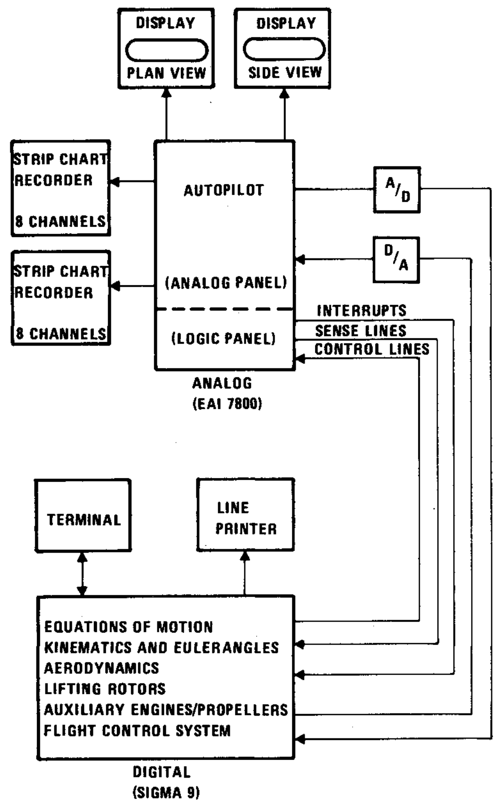

Fig. 2 Block diagram of hybrid computer simulation.

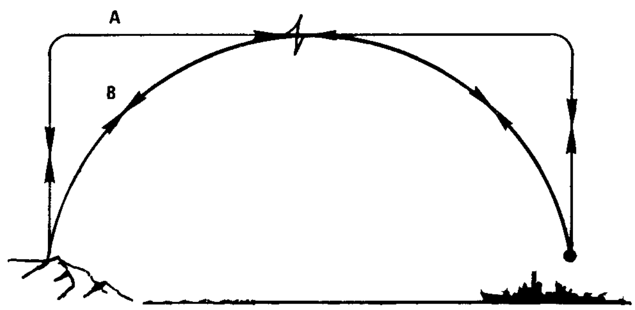

Fig. 3 Typical mission profiles.

autopilots are used to regulate the speed and altitude of the vehicle through its controls in forward and vertical motions. The fuel consumed by the vehicle during a specific flight, such as hover, cruise, or V/STOL mode, is determined from the fuel flow characteristics of the engines that drive the lifting rotors and propellers. Typically, the total power used by the vehicle is computed instantaneously during the simulated flight to obtain the corresponding rate of fuel consumption as well as the total fuel consumed up to that instant of time. These computations facilitate evaluation of vehicle performance characteristics, particularly in short-haul missions where V/STOL modes of flight are frequent and constitute a significant part of the operating time.

The preceding simulation scheme was set up on a hybrid computer formed by connecting an EAI 7800 analog computer with a Sigma 9 digital computer, as shown in Fig. 2. Most of the computation is done on the digital machine, while the autopilot and display circuits are set up on the analog computer. Both input and output data can be recorded on the strip chart recorders.

Mission A: Unloading a Ship Offshore

A short-haul mission was simulated where the HLA is used to transport payload units, each weighing 75 tons, from ship

Table 1 Breakdown of flight time and fuel consumption in a cycle

Mission profile A: Cruise altitude = 500 ft; mission range = 3 nautical miles

Flight mode	Flying weight (x1000 lb)	Distance (nautical mile)	Time (sec)	Fuel flow (lb/sec)	Fuel consumed (lb)
Accelerate vertically to cruise altitude	30	0	40	. . .	115
Accelerate forward to cruise speed	30	0.72	60	. . .	150
Cruise	30	2.00	122	2.92	355
Decelerate to hover	30	0.28	104	. . .	262
Descend to hover above ship	30	0	50	. . .	120
Hover	30	0	60	2.64	158
Payload pick-up					
Hover	180	0	60	5.28	317
Accelerate vertically to cruise altitude	180	0	42	. . .	230
Accelerate forward to cruise speed	180	0.35	29	. . .	140
Cruise	180	2.45	149	4.44	661
Decelerate to hover	180	0.20	33	. . .	187
Descend to hover above shore	180	0	47	. . .	230
Hover	180	0	60	5.28	317
Payload deposit					
Hover	30	0	60	2.64	158
Total		6.0	916		3400

to shore. Each cycle involved a sequence of tasks in which the vehicle would take off from shore and achieve a specified altitude and its cruising speed of 60 knots, where permissible, and fly toward the ship located at a distance. On reaching the ship, the HLA would descend and decelerate to hover above the ship to pick up the payload and fly back to shore and deposit the payload. Figure 3 shows typical mission profiles simulated in this study. The corresponding simulation output is also recorded on strip chart recorders (Fig. 4), and a breakdown of flight time and fuel consumption characteristics in a typical cycle is given in Table 1. A summary of these results is shown in Fig. 5 for various values of altitude and range. It is found that having thrust reversal capability in the auxiliary propellers reduces the cycle time.

Mission B: Logging

A typical logging mission was simulated to estimate the time required for the HLA to transport logs, assumed to be units of 75 tons, from a point 1000 ft high to a point on the ground at a horizontal distance of 4000 ft. The actual trajectories of the HLA both in the forward and return trips are shown in Figs. 6a and 6b. However, one can attempt to improve the performance of this vehicle by flying over an optimal flight path determined for this mission.

HLA Dynamic Stability

A linear system model that describes the longitudinal dynamics of the HLA with or without a payload, following a disturbance in its equilibrium flight path corresponding to hover or forward flight, is used to examine the stability characteristics of that configuration. Such a model has been derived[4] by linearizing the nonlinear equations of motion about an arbitrary trim point. The resulting perturbation equations describing the HLA-payload motion in the longitudinal direction only are considered here, and they are rearranged in the state variable from $\dot{x} = \underline{A}\, x$, where the state vector, $x^T = [\Delta u \Delta w \Delta q \Delta \Theta \Delta u_L \Delta x_L]$ consists of perturbations in vehicle and payload state variables. To examine the stability of the vehicle alone in the absence of the payload, a fourth-order dynamic model has been derived[5] to describe only the vehicle longitudinal motion. For specified design and flight conditions (see Table 2) the eigenvalues of the corresponding system matrix are shown in Tables 3 and 4. Typically, vehicle modes consist of a stable oscillation in forward velocity and pitch rate, and convergence of vertical and forward speeds. It is found that with increasing forward speed, the damping ratio of the oscillation increases significantly because of the corresponding increase in damping in pitch of the vehicle.

For a case in which a 75-ton payload is suspended from the vehicle, the corresponding modes and mode shapes of the configuration are as shown in Fig. 7. The resulting motion of the vehicle and payload has been determined from an equivalent analog computer simulation of the system modes. The higher frequency oscillation (mode 1) consists of coupled motion of the two bodies and is induced by the payload. Increasing length of the suspension cable tends to decrease the frequency of this oscillation, similar to that of a double pendulum. The remaining modes are similar to those inherent

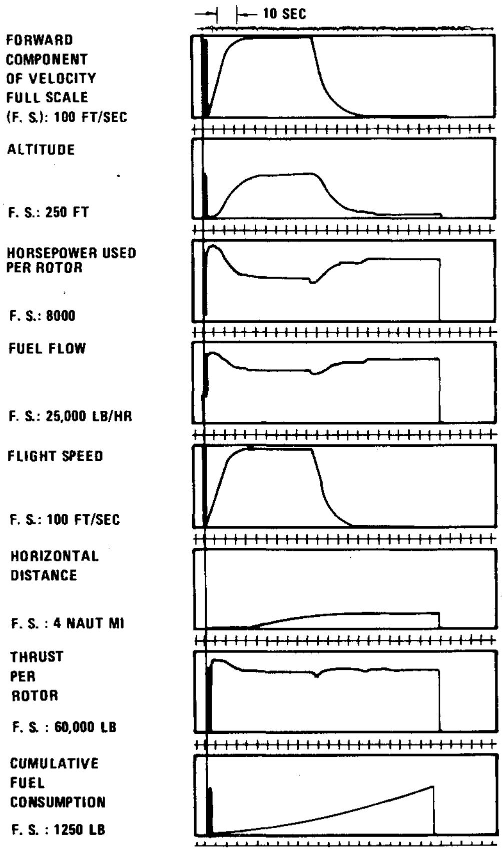

Fig. 4 Simulation output for profile B (flying weight = 180,000 lb).

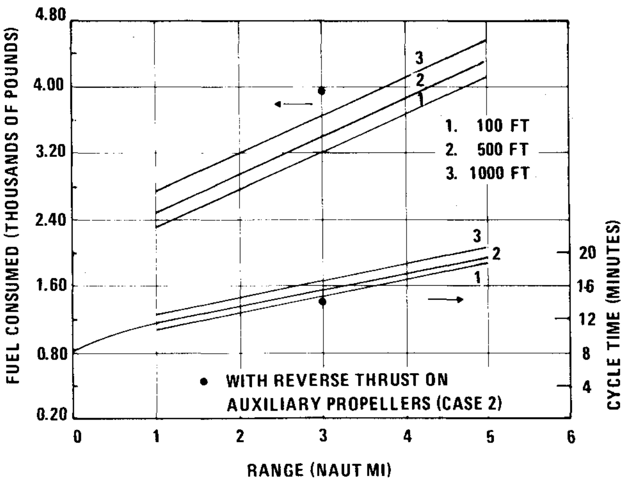

Fig. 5 Summary of performance data for profile A.

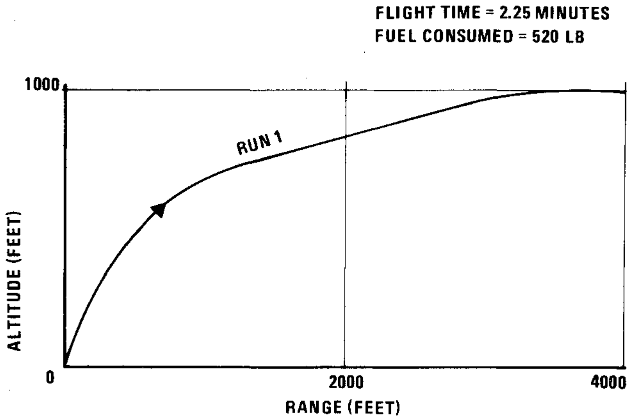

Fig. 6 a) Trajectory of forward trip of the HLA.

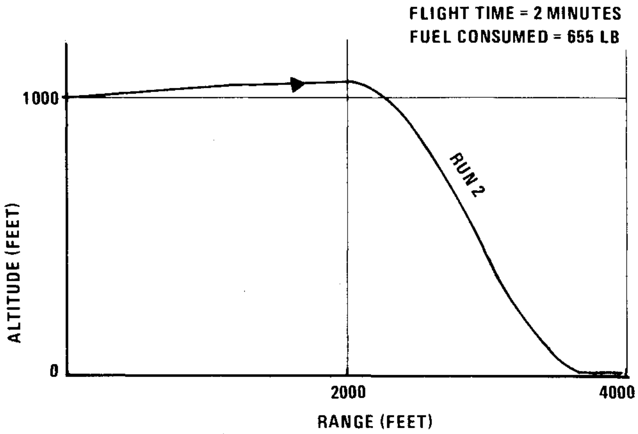

Fig. 6 b) Trajectory of return trip of the HLA.

to the vehicle. The effect of varying forward speed, length of the suspension cable, location of the payload suspension point (Z_s), and mass of the payload on the modes of the system is shown in Tables 5-7.

It is observed that possible instabilities of the system are in the form of a divergent mode-1 oscillation induced by the suspended payload and a divergence in forward speed of the vehicle. It is found that these modes are unstable in forward flight at speeds around 30 knots and tend to be so for increasing values of payload mass and length of the suspension cable. It is important to note that these stability characteristics are predicted by using preliminary aerodynamic data. Further investigations are necessary to verify these trends toward instabilities.

HLA Control Concepts

The forces and moments required to control the vehicle in all its rigid body degrees of freedom can be obtained by changing the lifting rotor thrust vectors as well as the thrust generated by the propellers, in unison or differentially. The tail surfaces can provide additional control moments in yawing and pitching. Typically, for the configuration in Fig. 1, there are 19 control variables that can be systematically combined for controlling the vehicle in all its flight modes, including precision hover. For each degree of freedom, it is possible to produce a control force or moment in a number of ways. For instance, a yawing moment can be produced by 1) differential collective pitch on the auxiliary propellers, 2) differential longitudinal cyclic pitch on the lifting rotors, 3) differential lateral cyclic pitch on the lifting rotors, and 4) deflection of tail control surfaces.

A particular choice of these options in a sequence or in unison is dependent upon the flight and operating conditions. Furthermore, the rate limits of control application, control authority limits, and dynamic responses of the control actuation systems are all a part of the selection and combination process involved in developing an HLA control concept.

Goodyear Aerospace has developed and evaluated a number of different control concepts for the HLA and is progressing toward the definition of a control-configured HLA. It has been found that a rather critical control problem is to hover precisely in the presence of atmospheric disturbances when the vehicle is near neutral buoyancy, which may occur while it is picking up a payload and is low on fuel. In this condition, the upward thrusts on the lifting rotors are small, and hence thrust vectoring is ineffective. Consequently, it is suggested that the lifting rotors be designed with negative thrust capability so that large control forces and moments can

Table 2 Estimated physical and aerodynamic data for HLA/payload configuration

m_v = 6913 slugs
m_L = 4663 slugs (nominal)
Z_C = 41.78 ft
ℓ = 100 ft (nominal)
Z_S = 60 ft
B = 185279 lb

$X_{\dot{u}}$ = −756 slugs
$Z_{\dot{w}}$ = −6612 slugs
$Z_{\dot{q}} = M_{\dot{w}}$ = −98, 746 slug-ft^2
I_{yy} = 78691114 slug-ft^2
$M_{\dot{q}}$ = −64027287 slug-ft^2

Overall length = 453 ft
Maximum diameter = 107 ft
Maximum width = 230 ft
Overall height = 125 ft
Envelope volume = 2,652,000 ft^3

Quantity[a]	Without payload			With payload		
	V = 0 knots	V = 30 knots	V = 60 knots	V = 0 knots	V = 30 knots	V = 60 knots
X_u	−26	−31	−76	−143	−90	−157
X_w	0	0	0	0	0	0
X_q	−2593	−1555	−9044	−197	2426	−21
Z_u	60	−136	242	78	−740	−308
Z_w	−892	−3905	−6568	−1332	−3905	−6476
Z_q	11803	−190167	−362991	16632	−215266	−389484
M_u	−1635	−119	−5875	−6709	3934	−3144
M_w	8337	90253	167508	12622	90035	167689
M_q	-3.187×10^6	-3.653×10^7	-6.922×10^7	-4.47×10^6	-3.602×10^7	-6.812×10^7

[a] These include contributions from hull and lifting rotors.

Table 3 Modes of heavy lift airship without a payload

V (knots)	Mode 1	Mode 2	Mode 3
0	$-0.012 \pm 0.234\,i$ (ζ = 0.05, ω_n = 0.235)	−0.066 (w)	−0.0033 (u)
30	$-0.109 \pm 0.188\,i$ (ζ = 0.50, ω_n = 0.218)	−0.341 (w)	−0.0027 (u)
60	$-0.165 \pm 0.110\,i$ (ζ = 0.83, ω_n = 0.199)	−0.661 (w)	−0.0122 (u)

Table 4 Modeshapes of heavy lift airship without a payload

V (knots)	Mode	Modeshape
0	$-0.012 \pm 0.2341\,i$	Δu = 1.0 (180°), Δw = 0.17 (54°), Δq = 0.02 (−173°), $\Delta\theta$ = 0.08 (94°)
	−0.066	Δu = 0.14 (180°), Δw = 1.0 (180°)
	−0.0033	Δu = 1.0 (0°), Δw = 0.07 (0°)
60	$-0.165 \pm 0.110\,i$	Δu = 1.0 (−3°), Δw = 0.52 (−102°), Δq = 0.007 (−127°), $\Delta\theta$ = 0.035 (19°)
	−0.661	Δu = 0.28 (180°), Δw = 1.00 (180°), Δq = 0.006 (0°), $\Delta\theta$ = 0.01 (180°)
	−0.0122	Δu = 1.00 (0°), Δw = 0.038 (0°)

Table 5 Effect of varying length of suspension cable on modes of HLA-payload configuration in forward flight (V = 30 knots)

ℓ(ft)	Mode 1	Mode 2	Mode 3	Mode 4
1	−0.0010 ±7.081 i	−0.095 ±0.214 i	−0.311	0.0028
21	+0.89E−03 ±1.536 i	−0.093 ±0.213 i	−0.310	0.0028
41	+0.0026 ±1.094 i	−0.0907 ±0.211 i	−0.307	0.0028
61	+0.0041 ±0.893 i	−0.0887 ±0.210 i	−0.306	0.0028
81	+0.0055 ±0.771 i	−0.0870 ±0.209 i	−0.304	0.0028

Table 6 Effect of varying location of the payload suspension point on the modes of HLA-payload configuration in forward flight ($V = 30$ knots)

ℓ (ft)	Z_s (ft)	Mode 1		Mode 2	Mode 3	Mode 4
	0	-0.0073	±1.022 i	-0.0812 ± 0.153 i	-0.348	0.0123 (u)
50	20	-0.0048	±1.014 i	-0.0854 ± 0.174 i	-0.355	0.008
	40	+0.95E-03	±1.002 i	-0.0883 ± 0.194 i	-0.320	0.005
	60	+0.0036	±0.987 i	-0.0894 ± 0.211 i	-0.307	0.0027
	0	-0.0045	±0.717 i	-0.0820 ± 0.153 i	-0.352	0.0123
100	20	-0.0013	±0.711 i	-0.0845 ± 0.174 i	-0.334	0.0080
	40	+0.0026	±0.702 i	-0.0855 ± 0.192 i	-0.317	0.0049
	60	+0.0069	±0.691 i	-0.0849 ± 0.208 i	-0.302	0.0027

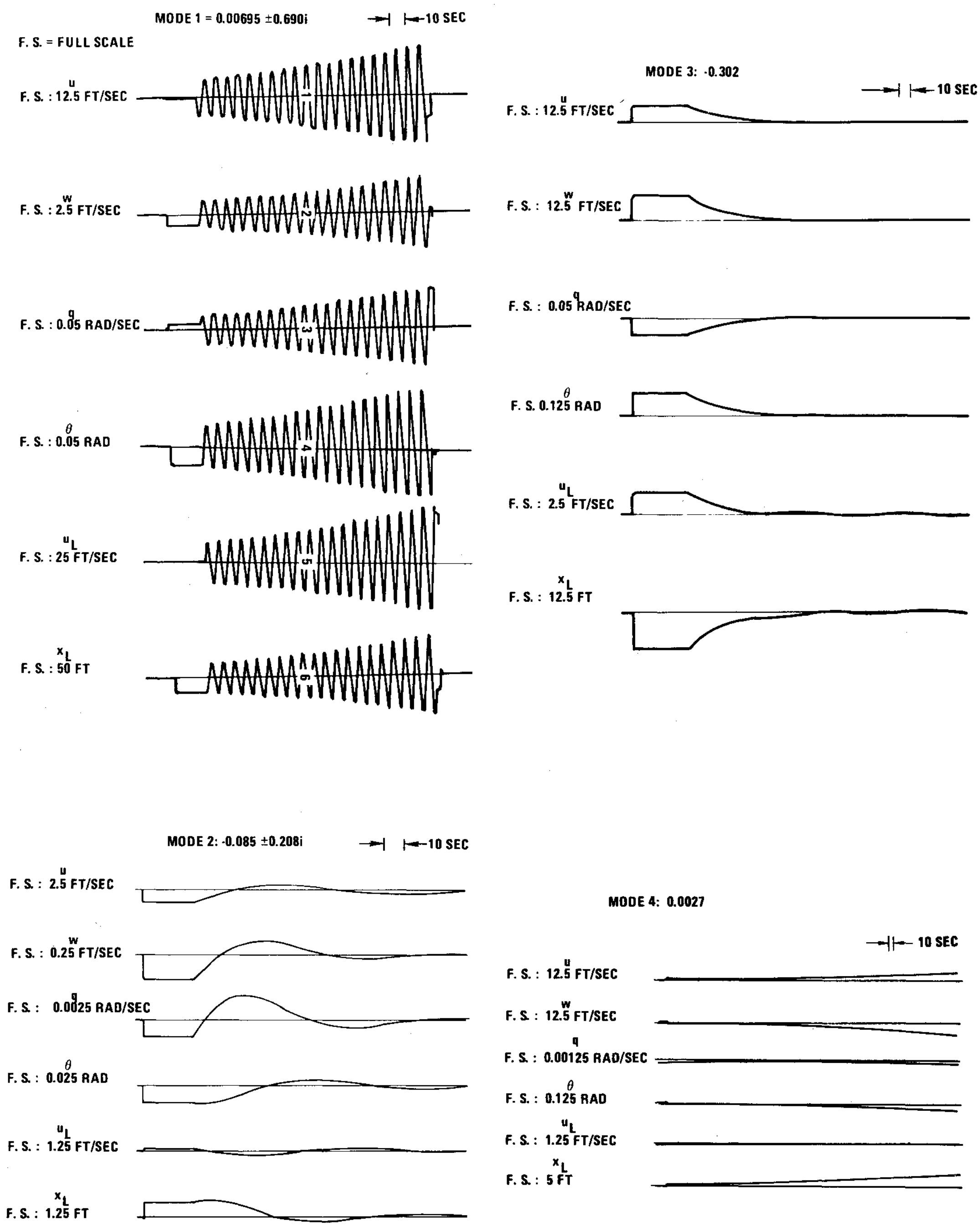

Fig. 7 Modes and modeshapes of the HLA-payload system in forward flight ($V = 30$ knots, $m_L = 4663$ slugs, $Z_s = 60$ ft, $l = 100$ ft).

Table 7 Effect of varying payload mass on modes of HLA-payload configuration in forward flight (l = 100 ft, Z_s = 60 ft)

V (knots)	m_L (slugs)	Mode 1	Mode 2	Mode 3	Mode 4
	1000	-0.0224 ± 0.601 i	-0.100 ± 0.201 i	-0.338	-0.0063
	2000	-0.0066 ± 0.630 i	-0.0949 ± 0.205 i	-0.327	-0.0027
30	3000	0.00 ± 0.655 i	-0.0906 ± 0.206 i	-0.317	-0.11E-03
	4000	0.0043 ± 0.678 i	-0.087 ± 0.207 i	-0.308	0.0018
	5000	0.0078 ± 0.698 i	-0.084 ± 0.207 i	-0.300	0.0033
	1000	-0.0548 ± 0.602 i	-0.149 ± 0.143 i	-0.634	-0.023
	2000	-0.0239 ± 0.633 i	-0.136 ± 0.152 i	-0.619	-0.0189
60	3000	-0.0121 ± 0.660 i	-0.125 ± 0.157 i	-0.605	-0.0159
	4000	-0.00463 ± 0.684 i	-0.116 ± 0.160 i	-0.593	-0.0137
	5000	0.0011 ± 0.706 i	-0.108 ± 0.162 i	-0.581	-0.012

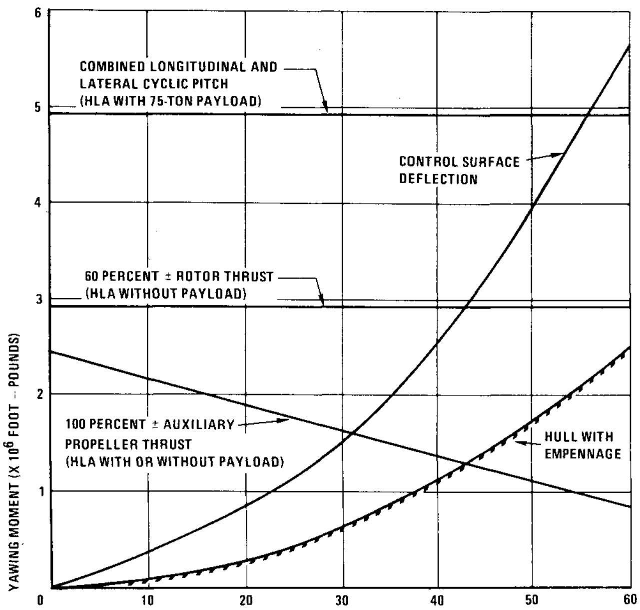

Fig. 8 Control moment in yaw for an HLA at 20-deg sideslip.

be produced by equal and opposite thrusts on the four lifting rotors such that no net vertical force is produced.

Although several options for producing a specific control force or moment exist, many of them may be eliminated by considering the vehicle operational concepts. For instance, in the ferry mode, where the HLA is not carrying any payload, it could be controlled like a conventional airship, particularly during cruise and short takeoff and landing, while the lifting rotors would be used for control augmentation only. However, hovering in most wind conditions would require controlling the vehicle by vectoring thrusts on the lifting rotors since the empennage surfaces would not be effective.

Figure 8 illustrates typical control moments that can be produced by various means to overcome the aerodynamic yawing moment of an HLA with or without a 75-ton payload and sideslipping at 20 deg at various airspeeds. The control surfaces on the empennage have conventionally been sized to overcome the aerodynamic yawing moment of the hull with empennage configuration sideslipping at 20 deg at all airspeeds, as shown. However, at low speeds, particularly in responding to atmospheric disturbances, this mode of control is ineffective. It is observed that when the HLA is carrying a 75-ton payload, thrust vectoring may be effectively used at all airspeeds to produce a yawing moment on the vehicle. But when the HLA is light, close to neutral buoyancy, vectoring rotor thrusts were found to be ineffective in station keeping without thrust reversal capability up to 60%. The auxiliary propellers with reverse thrust capability up to 100% could also be used to produce a control moment in yaw, particularly at low airspeeds. In fact, by using this approach, the vehicle with or without a payload may be trimmed up to 45 knots at 20-deg sideslip, as shown in Fig. 8.

It is observed that the selection of a particular option or sequence of options is strongly dictated by the operating mode, and hence there are limited choices. These may be further narrowed by performance considerations in some cases.

Concluding Remarks

Goodyear Aerospace has been conducting flight dynamics analyses and simulations of the HLA to develop the software needed in the design and analyses phase of the subsequent hardware program. However, the lack of aerodynamic data has limited the use of these analytical tools at present. Consequently, it should be noted that the results presented in this paper are based on available aerodynamic data which are preliminary in nature. The company is pursuing further studies of HLA flight dynamics and intends to look into the aerodynamics of multiple-rotor configurations, aeroelastic stability and aerodynamic interference effects of the HLA, and various schemes for payload suspension.

References

[1] "Alberta Modern Airship Study Final Report," prepared for Alberta Ministry of Transportation, Goodyear Aerospace Corp., Akron, Ohio, GER-16559, June 1978.

[2] Mettam, P.J., Hansen, D., Byrne, R.W., and Ardema, M.D., "A Study of Civil Markets for Heavy Lift Airships," AIAA Paper 79-1579, Palo Alto, Calif., July 11-13, 1979.

[3] Nagabhushan, B.L., "Equations of Motion of Heavy Lift Airship with a Simply Suspended Payload," Goodyear Aerospace Corp., Akron, Ohio, GER-16443, March 1977.

[4] Nagabhushan, B.L., "Linear System Definition of Heavy Lift Airship/Payload Flight Dynamics," Goodyear Aerospace Corp., Akron, Ohio, GER-16498, Dec. 1977.

[5] Nagabhushan, B.L., "Stability and Control Characteristics of Heavy Lift Airship/Payload Configuration," Goodyear Aerospace Corp., Akron, Ohio, GER-16573, Oct. 1978.