Thrust-Vectored Takeoff, Landing, and Ground Handling of an Airship

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Takeoff, landing, and ground-level maneuverability characteristics of a modern airship having twin, vectorable thrustors were analyzed using an advanced airship flight simulation. The effects of thrust tilting on tail clearance, angle of attack, and ground distance were examined for several V/STOL modes in which the airship was light, heavy, or in equilibrium. The significance of prevailing winds in such cases to improve the vehicle's performance is illustrated. Airship response to control inputs and wind disturbances in near-ground operations were simulated. In the latter case, it was found that ground plane excursions of the vehicle could be reduced by selective use of thrust application rate and operator time lag. The consequences of thrust vectoring on the overall vehicle system design and operation are discussed. The need for heading and altitude autopilots as well as a state-of-the-art wind vector monitor at the pilot station are also presented.

Nomenclature

h = reference altitude, ft
$\dot{h}$ = vertical velocity, ft/s
h_c = commanded altitude, ft
$I_{xx,yy,zz}$ = moment of inertia about reference body axes system whose origin is at the vehicle center of mass, slug-ft^2
L,M,N = rolling, pitching, and yawing moments, respectively, ft-lb
p,q,r = roll, pitch, and yaw velocity of the vehicle, respectively, rad/s
T_{max} = maximum thrust, lb
u,v,w = longitudinal, lateral, and vertical components of vehicle translational velocity in the x, y, and z directions of the reference body axes, respectively, ft/s
V = vehicle airspeed, ft/s
V_w = wind velocity, knots
x,y,z = coordinates of a point in the reference body axes system, ft
β = sideslip angle, deg
δ_e = elevator deflection, deg
η = throttle setting
θ = pitch attitude of the vehicle, deg
θ_c = commanded pitch attitude, deg
θ_t = longitudinal tilt of the thrust vector, deg
ψ = yaw attitude of the vehicle, deg

Introduction

RECENTLY there has been a growing interest in modernizing conventional airships, as is evident from new designs and hardware programs in progress.[1,2] A principal facet of this evolution has been to incorporate vectorable thrusting devices that are mounted on outriggers on either side of the airship car. Potential control concepts based on thrust vectoring and their impact on performance of a typical airship have been investigated in Ref. 3. In that study and others[4] it was found that tiltable thrust vectors for lift, cruise, or control tend to provide an airship with greater operational flexibility, especially during takeoff and landing.

In the present case, use of tiltable thrust vectors in conjunction with conventional aerodynamic controls was examined closely in V/STOL flight modes and during ground handling. Particular attention was given to identify and quantify marginal improvements in vehicle performance resulting from using the aerodynamic controls in a complementary role. The significance of reverse thrusting, rate, and time lag associated with thrust application, and prevailing winds, in enhancing vehicle response and flight characteristics were also investigated. The following sections include a description of the example airship, its flight simulation model, an analysis of its V/STOL and ground-handling characteristics, and overall vehicle design considerations.

Airship Configuration

The modern airship considered herein was assumed to be in the class of Goodyear GZ-20 blimps. It was configured to have two vectorable ducted fans attached to its car, one on either side (Fig. 1). These fans were assumed to be mounted such that they could be tilted up or down in the longitudinal vertical plane. The ability to reverse up to 50% of the thrust generated by these ducted fans has been assumed in this study.

Physical properties of the example airship (Table 1) were estimated on the basis of the following assumptions. The ducted fans would be powered by lighter and more powerful engines than the GZ-20 airship engines. Further, composite materials would be extensively used in the car structure, ducted fans, and outrigger supports. Also, the weight of ducted fans, outriggers, and any additional fuel carried would be mostly offset by the preceding improvements. Basically this configuration was chosen to facilitate conducting analyses and parametric evaluations rather than assessing a point design.

Flight Simulation Model

A mathematical model of the airship configuration presented above has been generically developed previously. It was set up on a hybrid computer system consisting of a Sigma-9 digital computer and an EAI 7800 analog computer. The bulk of the computation was done on the digital machine, while the analog computer was used to vary gains on autopilots and record input and output variables on strip charts and an x-y plotter.

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Complete rigid-body motion of the airship was simulated using general nonlinear equations of motion.[5,6] Basically, the airship hull was assumed to be a rigid body supporting the car, ducted fans, and outrigger members using a hard structure. External forces and moments acting on the vehicle due to gravity, buoyancy, aerodynamics, and control inputs were included in this model. Translation of the airship was described in terms of its velocity components u, v, and w along the x, y, and z reference body axis whose origin was assumed to be at the vehicle center of buoyancy. The rotational motion of the vehicle was described by its angular velocity components p, q, and r about these same reference axes. The orientation of the vehicle was described by Euler angles ϕ, θ, and ψ, which locate the reference body axes with respect to a local horizon system.

Aerodynamic properties of the airship were modeled[7,8] within the existing data-base. As a first approximation the normal-force and pitching-moment characteristics of the vehicle were assumed to be equal to its side-force and yawing-moment characteristics, respectively. The damping moments due to pitching and yawing of the vehicle were estimated[9] from corresponding derivative data. Similarly, acceleration-dependent aerodynamic forces and moments on the airship were estimated[7] and included.

The lift/cruise ducted fans mounted one on either side of the airship car were modeled as pure force generators with a nominal 50% reverse-thrust capability. Each of the ducted fans was assumed to generate a nominal, static thrust of 1200 lb. The corresponding thrust magnitudes were corrected for airspeed effect based on empirical and experimental data. The blade pitch control of each fan was assumed to be linearly proportional to the thrust generated by that unit. The corresponding installed power required per fan was estimated to be 300 hp. This power level is representative of this class of airship powerplants. It should be noted that no allowance was made here for the associated aerodynamic interference effects between the airship envelope and the ducted fans. In the simulation, the tilt rates of these thrust vectors were set nominally at 5 deg/s within the range of +90 deg (up) to −120 deg (down). Maximum thrust change from +1200 to −600 lb was assumed to occur in 10 s in all cases, except where specified otherwise. Both thrust-vector tilt rate and thrust application rate assumed here were based on engineering judgment and are not necessarily optimal. Consequently, they have been varied in the simulation to determine their effect on vehicle control and maneuverability.

Fig. 1 Example airship configuration.

Several autopilots were designed and used to simulate the desired flight conditions of the airship. For instance, an altitude autopilot was used during V/STOL modes of flight to control the vehicle altitude. Similarly, a yaw autopilot was used to maintain vehicle heading during ground-handling simulation. These autopilots consisted of position or attitude and rate feedback only. It should be observed that all possible options in using the twin thrust vectors from the car-mounted ducted fans cannot be fully explored by a computer simulation alone. Pilot-in-the-control-loop simulation would perhaps give better insight in this regard, particularly if these thrust vectors are to be operated independently. In the present case, however, the two thrust vectors were assumed to be operating synchronously while tilting ($\pm\theta_t$) to give corresponding control forces. The airship elevator and rudder controls were assumed to be activated individually with the corresponding control input. For instance, the yaw control command was assumed to actuate the rudder deflection. Similarly, the altitude autopilot was assumed to command either the elevator or the thrust vectors as specified during the simulation.

Thrust-Vectored Takeoff

The preceding flight simulation model of the airship was used to investigate the advantages of thrust-vector control during vertical or short takeoff flights under various operating conditions. Figure 2 shows the effect of thrust vectoring on vehicle takeoff trajectory. Typically, larger uptilt of the thrust vectors has been found to move the airship to a higher altitude over a shorter ground distance but not

Table 1 Estimated physical properties of example airship

Item	Description/value
Airship	
Envelope volume (stretched), ft^3	235,550
Overall length, ft	196
Maximum diameter of envelope, ft	47
Fineness ratio	4.1
Fin configuration	X (45 deg inclination)
Center-of-buoyancy location (nominal)	93.3 ft from bow
Center-of-gravity location (nominal)	14.1 ft below Center-of-buoyancy
Propulsion	
Ducted fan location	1.1 ft ahead of Center-of-gravity, 28.2 ft below Center-of-buoyancy
Maximum continuous thrust, lb	1200
Maximum reverse thrust, %	50
Thrust-vector tilt rate (nominal), deg/s	5
Time for maximum thrust change, s	10
Tilt limit with reference to horizontal	90 deg (up)/120 deg (down)
Gross weight (nominal), lb	13,600
Static lift (nominal), lb	13,400
I_{xx}, slug-ft^2	168,097
I_{yy}, slug-ft^2	899,477
I_{zz}, slug-ft^2	828,639

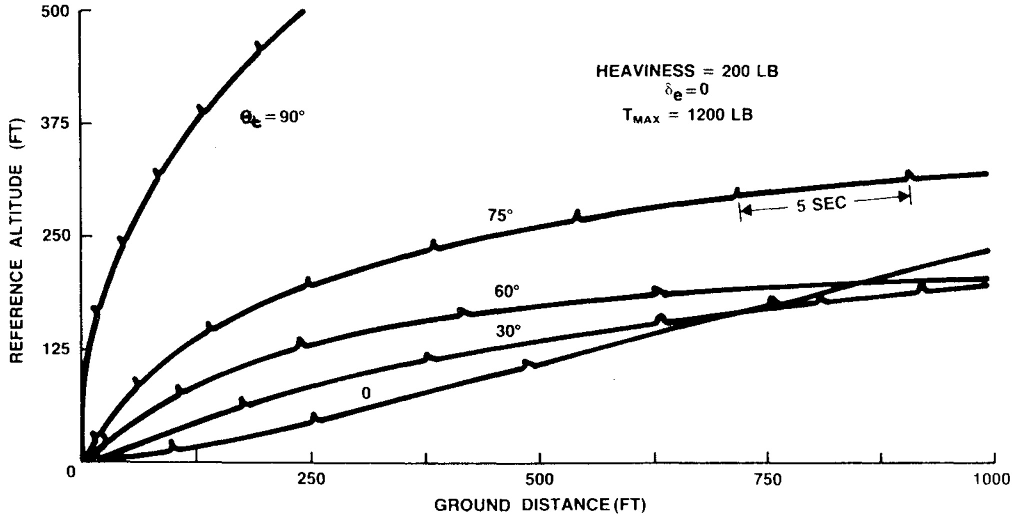

Fig. 2 Thrust-vectoring effect on takeoff trajectory.

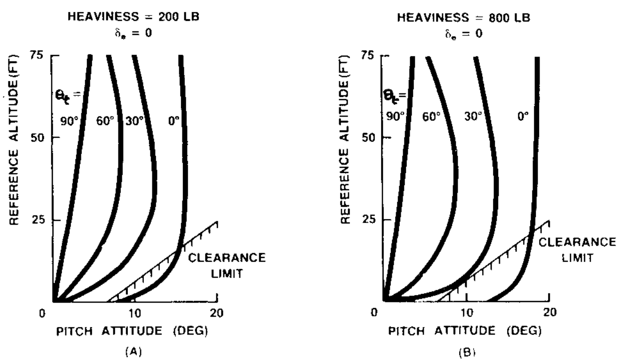

Fig. 3 Thrust-vectoring effect on tail clearance during takeoff.

necessarily in less time. This is because of the lower flight speed attained[3] by the vehicle while it is encountering its broad side drag and apparent mass effects. It should be noted that the incremental altitude changes accomplished with incremental changes in thrust-vector tilt angles are strongly dependent on the corresponding initial tilt angles. For instance, consider the vehicle altitude at a ground distance of 250 ft for the various thrust-vector tilt angles shown in Fig. 2. Increasing the tilt angle from 30 to 60 deg in such a case results in an altitude increment of 50 ft, while the same increment from 60 to 90 deg produces an altitude increment of 375 ft. Consequently, to realize sensitive height control from thrust vectoring during takeoff, an uptilt angle in the range of 60-90 deg seems necessary.

The tail clearance required for conventional takeoff prohibits an airship from attaining steep climb angles at liftoff, in such a case the airship has a long ground run before it can clear obstacles. However, thrust vectoring has been found to eliminate this requirement even for a heavy vehicle (Fig. 3). For the example airship, a modest uptilt of its thrust vector to 30 deg provided ample clearance. Light head winds prevailing at takeoff have also been found to have a favorable effect in this regard (Fig. 4). Basically, in such a case the vehicle airspeed is sufficient to generate adequate aerodynamic lift to overcome its heaviness and get airborne over a shorter ground distance without a steep climb. Another approach, which is practiced during a conventional takeoff, is to use lower throttle settings (Fig. 5) on the thrusting devices such that the vehicle pitch attitude remains small until a safe clearance height has been achieved. Of course, the associated ground run at the lower throttle operation is also longer. For the example airship, takeoff with the throttle setting higher than 50% was found to result in the tail hitting the ground plane.

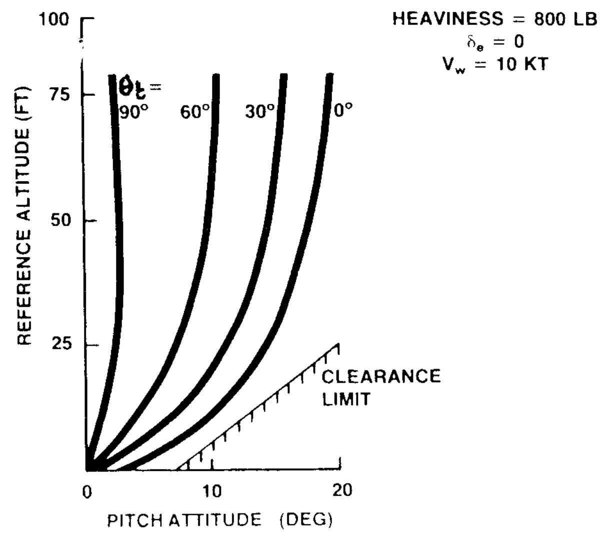

Fig. 4 Headwind effect on tail clearance during takeoff.

In a conventional takeoff the airship angle of attack does not exceed a few degrees although the vehicle develops large pitch attitudes. However, in thrust-vectored takeoffs, large angles of attack are attained by the airship especially at higher tilt angles of the thrust vectors (Fig. 6). In a vertical takeoff with the thrust vectors tilted up 90 deg, the corresponding vehicle angle of attack was found to be over −90 deg. As shown, the airship in such a case developed typically low airspeeds compared to those at smaller angles of attack attained at lower tilt angles. Therefore, the associated dynamic pressures are small. Consequently, the corresponding aerodynamic loads and their distribution over the airship envelope are not of concern. However, the airflow does separate over the envelope at these larger angles of attack which tend to increase its drag. Also, the fins and control surfaces experience aerodynamic stall which renders them ineffective and increases their drag. This aspect needs careful investigation, both analytical and experimental, before one can design efficient thrust-vectoring schedules for takeoff and transition to cruise. It is observed that these schedules become more important for a vehicle operating near its maximum heaviness, since the aerodynamic controls are then essential for orienting the airship to generate adequate aerodynamic lift and transit smoothly into cruise.

Thrust-Vectored Landing

Landing with vectored thrust was simulated for the vehicle operating under heavy, equilibrium, or light conditions.

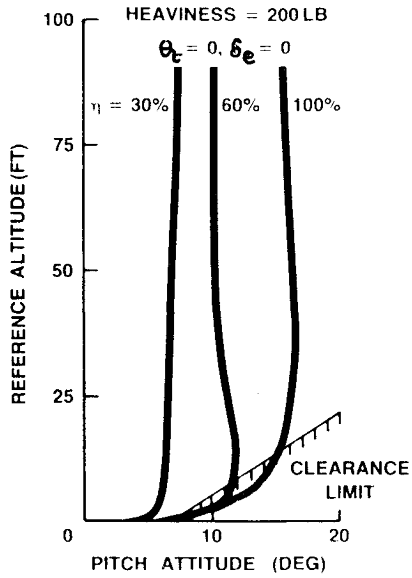

Fig. 5 Throttle setting effect on tail clearance during takeoff.

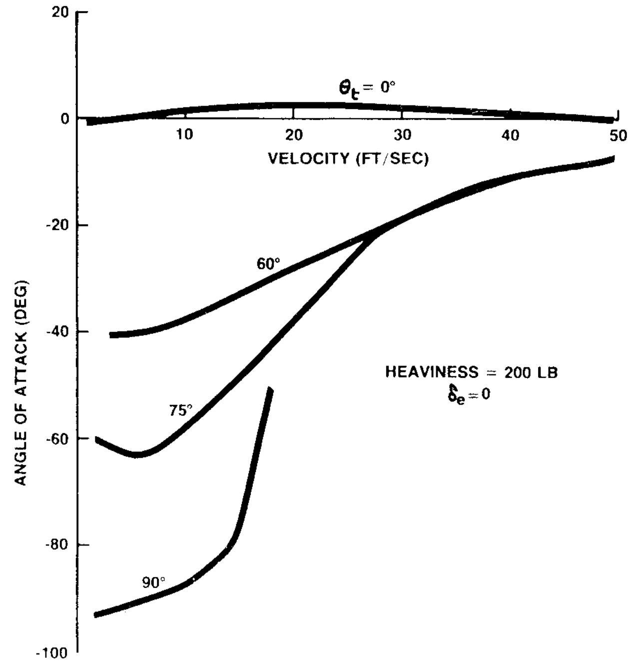

Fig. 6 Angle-of-attack variation during thrust-vectored takeoff.

Since there is no established touchdown criteria, the simulated landings were performed such that near-zero vertical speed was achieved at zero reference altitude. As illustrated previously,[3] the vertical component of the thrust vectors can be typically used to counter the heaviness or lightness of the vehicle. This obviates the need for developing aerodynamic lift during landing. Consequently, descent and flare may be performed at very low speeds. Further, the operator has great flexibility during the landing approach/descent phase and could attain a desired steep or shallow flight path leading to a touchdown. This aspect was investigated here by also considering the elevator control in a complementary role.

Figure 7 shows typical landing trajectories obtained by using elevator control at fixed thrust-vector angles. These were simulated using an altitude autopilot which commanded the elevator deflection alone. The initial condition in all cases was trim at a speed of 10 knots in level flight. In the absence of thrust vectoring ($\theta_t = 0$) the vehicle ground distance for landing was 2600 ft and flight time was 175 s. However, 90-deg downtilt of the thrust vectors in such a case was found to reduce the corresponding ground distance and flight time by one-half. However, this difference was nearly absent when a 10-knot head wind prevailed (Fig. 8). Here the same autopilot was found to be more effective since the vehicle airspeed was 20 knots. Consequently, steep descent flight paths were achieved with or without thrust vectoring. These results suggest that an operator should judiciously mix thrust-vectoring control with elevator control, depending upon prevailing wind conditions.

An altitude autopilot that commands the magnitude of thrust vectors at fixed tilt angles was used next to simulate airship landing trajectories (Fig. 9). It was found that at low approach velocities, a thrust-vector downtilt angle of at least −70 deg was necessary to cause vehicle descent that leads into a landing. Nearly a vertical descent trajectory was obtained at a −120 deg downtilt angle. Basically, these results indicate that landing can be performed without the use of an elevator either when it is ineffective or in an emergency. As noted previously, the airship was found to attain a large angle of attack during steep descent, similar to that in climb. Its consequences would be more critical while landing at or near maximum heaviness. The associated aerodynamic interaction with the ground plane and aerodynamic control effectiveness are issues beyond the scope of the present study. Incidentally, in a conventional heavy landing, the pilot could throttle back and descend steeply under gravity; however, this does not provide adequate aerodynamic control necessary during ground approach through touchdown.

Vehicle landing while it is in equilibrium or neutrally buoyant was also simulated using both positive and reverse thrust. For simplicity, the reverse-thrust-vectoring envelope was assumed to be a subspace of positive thrust. Typically, use of positive thrust at larger downtilt angles was found to yield a steeper descent leading to a shorter landing (Fig. 10). However, applying 50% reverse thrust at large uptilt angles was found to produce shallow flight-path angles, while at small uptilt angles it essentially produced braking action. It was found that for the same line of action (say +60 and −120 deg), using a positive thrust that is twice the reverse thrust decreased the corresponding ground distance by about one-half. Consequently, use of reverse thrusting for landing appears to be useful when a higher percentage of positive thrust can be reversed than is assumed here. Another factor to consider in an actual design is the quickness inherent to thrust reversing rather than thrust vectoring. For instance, turning the thrust vector 180 deg by using a typical mechanical drive may take 10-15 s, while changes in blade pitch and power setting associated with thrust reversing may be accomplished in 5-10 s.

Approach to landing a light airship at moderate flight speeds was also simulated. Typically, elevator control was used in a complementary role, while thrust vectors at fixed tilt angles were used as primary controls that drove the vehicle down (Fig. 11). It was found that significantly steeper descent trajectories at shorter ground distances could be achieved by using elevators deflected 20 deg down during the flight. Basically, in such a case the elevators control the vehicle flight-path angle as well as increase its downward lift, while the thrust vectors control its flight speed.

Based on the preceding landing simulation results it is observed that elevator control can be used successfully to augment the advantages of thrust vectoring for all heaviness conditions of the airship. However, vehicle landing using thrust vectoring and no elevator control is feasible when necessary.

Ground-Handling Characteristics

Ground handling of a conventional airship has always been a difficult task both for the pilot and ground crew. It is well known that after landing an airship the pilot continues

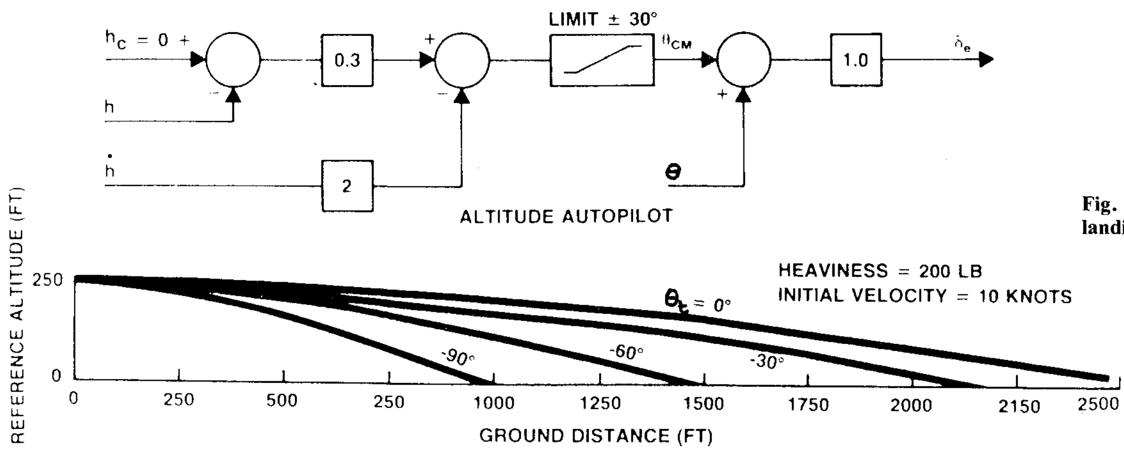

Fig. 7 Elevator-controlled landing trajectories.

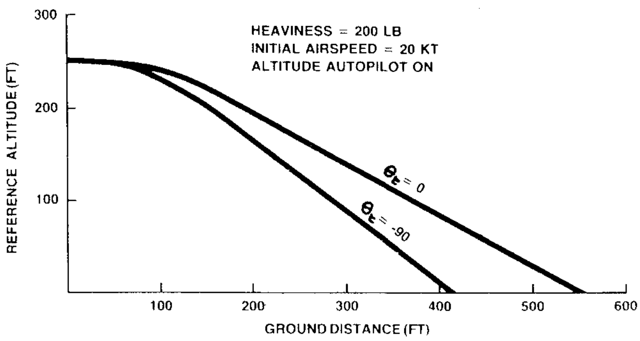

Fig. 8 Elevator-controlled landing into a 10-knot head wind.

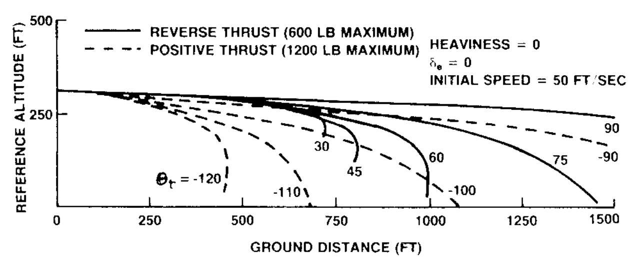

Fig. 10 Reverse-thrust effect on landing trajectories.

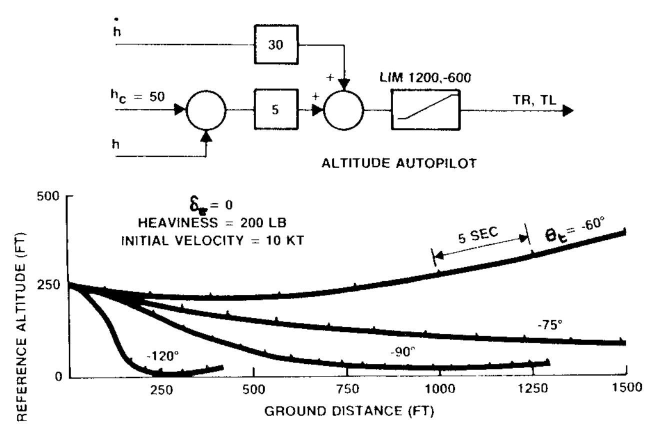

Fig. 9 Thrust-vector-controlled landing trajectories.

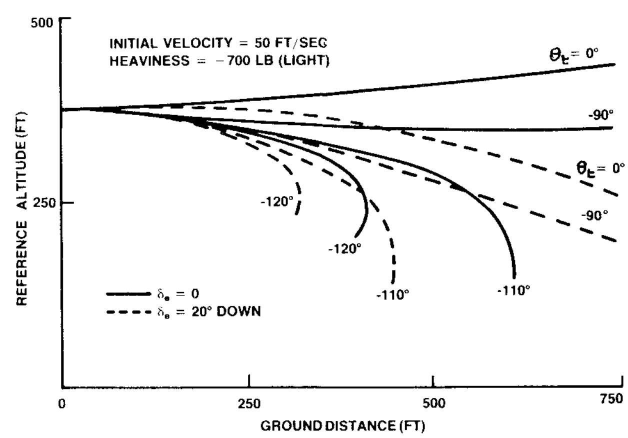

Fig. 11 Elevator control effect on thrust-vectored landing trajectories.

to fly into prevailing winds in order to maintain his ground position unless the vehicle is moored. Ofter mooring itself has been a problem due to shifting or gusting winds and inadequate control power to maneuver the airship to reach a desired position over ground. In the present investigation vehicle response to control inputs and wind disturbances typically experienced during ground handling were simulated to determine airship sensitivity to thrust control parameters.

Longitudinal response of the vehicle to various thrust application rates was simulated (Fig. 12) to assess its maneuverability in that axis. Comparing the vehicle motion following typical thrust application at a rate of 150 lb/s (case D) with that of instantaneous input (case A), it is observed that the former lags the latter by 3.7 s in reaching a specified longitudinal station. The reason for such a relatively short temporal separation is the large time constant associated with this type of vehicle.

Control of the airship vertical motion using conventional horizontal thrust is extremely limited during ground handling since the aerodynamic lift in such a case is small (Fig. 13). However, in a prevailing head wind the vehicle could be flown into it to generate some vertical control aerodynamically, as shown. Note that judicious use of thrust lag in response to the head wind (case C) could result in vertical motion alone with very little longitudinal displacement. However, this could be demanding on the operator. Obviously, using uptilted thrust vectors for vertical control is easier as it is relatively independent of prevailing wind conditions.

Airship response to a 15-knot cross wind was simulated for various thrust inputs (Fig. 14). In all cases a yaw autopilot was used to command the rudder deflection to head into the wind. It was found that using an instantaneous thrust input tends to cause a longer longitudinal excursion than lateral drift (case A). However, a 5-sec lag in application of the same thrust at a rate of 300 lb/s resulted in the vehicle developing a smaller overall radial drift. This can be understood by noting that in case C the initial absence of thrust and subsequent thrust buildup over a period allows the airship to turn into the wind. In case A, however, the same amount of turn is accomplished while the ship is being driven longitudinally by the thrust input; this tend to stretch the turn before heading into the wind. It should be noted that inherent, directional static instability of the airship plays a significant role in this regard. For instance, this vehicle's yaw response to a cross wind ($\beta = 90$ deg) would be to turn into the wind until the sideslip angle decreases to 60 deg. This corresponds to a stable equilibrium and the associated aerodynamic yaw moment is zero (Fig. 15). Further turning into the wind was accomplished in the preceding cases through rudder deflection.

Airship response to a 30-deg shift of a 15-knot head wind was also simulated for similar thrust inputs (Fig. 16). As before, a yaw autopilot was used to turn the vehicle into the wind. In this case, a 5-sec lag instead of instantaneous thrust application resulted in greater lateral drift of the vehicle. But the corresponding longitudinal drift was nearly equal. Vehicle response in a case where the thrust input was maintained at initial trim is also included for comparison (case D). It is clear that airship ground position cannot be maintained by using rudder alone, without applying the necessary additional thrust. In all cases it should be noted that the time to turn the vehicle into the wind is essentially the same. Therefore, the corresponding differences in airship excursions are basically due to the variations in thrust application rate and input time lag. As evident in case C, the time lag here was too long which allowed greater lateral drift. These results suggest that an operator or an autopilot could coordinate the turning control and thrust input such that the vehicle excursions are minimal for a given wind shift.

The preceding simulation results tend to illustrate vehicle sensitivity to thrust-related parameters. The ability to apply thrust instantaneously does not appear to be critical in limiting vehicle response to wind disturbances. In this regard, time lag associated with thrust application seems to have a greater effect. In other words, larger airship excursions could result from a pilot's inability to respond with the optimum time lag, rather than slower thrust application rates. Consequently, improvements in pilot cues should be considered. Better insight into using these control variables and developing operating procedures would require piloted simulations.

Vehicle Design Considerations

The above V/STOL and ground-handling simulation results bring out a number of items for potential consideration in an actual design. A brief discussion of these follows. One of the concerns of using car-mounted thrust-vectoring devices, such as tiltable ducted fans, is the effect of associated high-velocity slipstream impinging on the airship envelope. For instance, the ducted fan of the example airship produces slip-stream velocities as high as 200 ft/s while generating a thrust of 1200 lb. Not only does this increase the aerodynamic drag of the overall vehicle but also creates additional aerodynamic loading on parts of the envelope within their slipstreams. However, recent studies conducted by Goodyear Aerospace Corporation indicate that for small thrust-vector angles, the same slipstreams could be designed to increase the dynamic pressure over the empennage control surfaces and augment their control power at low speeds. Significant aerodynamic interference among the ducted fans, car, and envelope has also been observed in such analytical studies. Preliminary results have indicated that careful placement of the ducted fans relative to the car and envelope is necessary to minimize propulsive thrust degradation.

Another aspect of thrust-vectoring design is the range of available tilt angle and its dependence on associated powerplant location. Tilting the entire powerplant/ducted fan combination is one option, while driving the ducted fan from a stationary powerplant through gearing is another. The former involves complications in modifying gravity-based engine systems to permit large tilt angles, while the latter needs a more complex power transmission system. Consequently, selection of a particular option depends on the design criteria used.

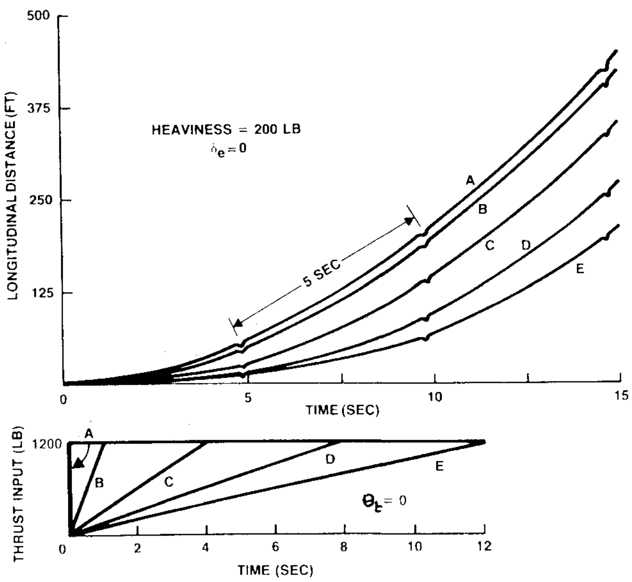

Fig. 12 Thrust rate effect on longitudinal maneuverability.

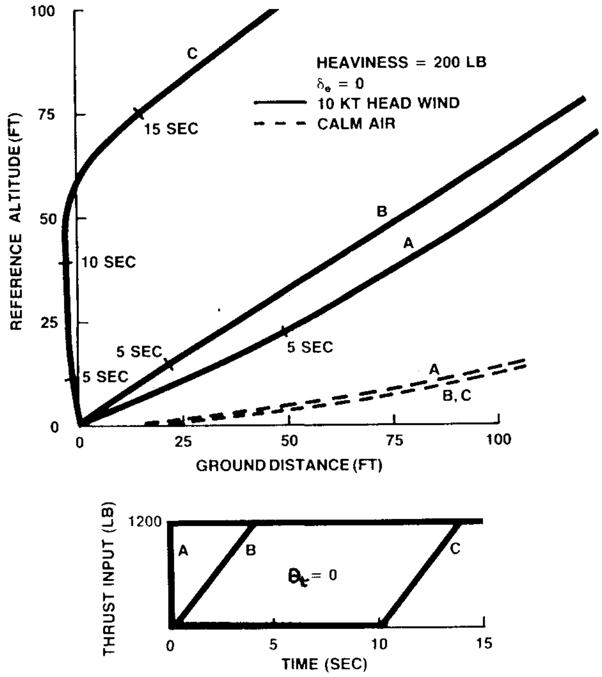

Fig. 13 Head wind effect on vertical plane maneuverability.

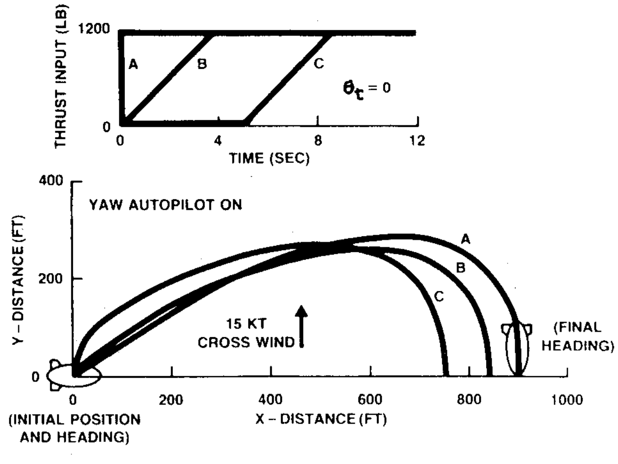

Fig. 14 Thrust rate and lag effects on airship response to a cross wind.

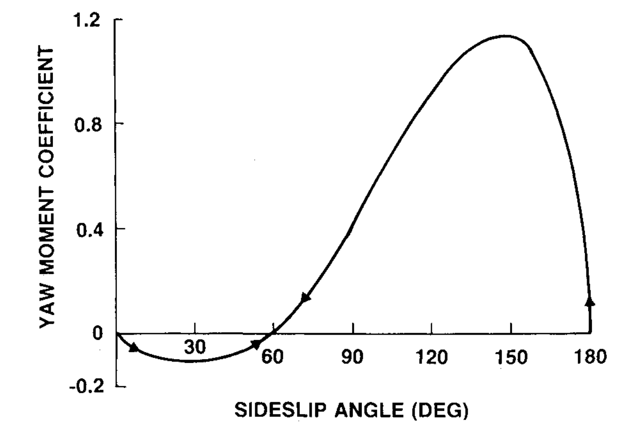

Fig. 15 Directional static stability of example airship.

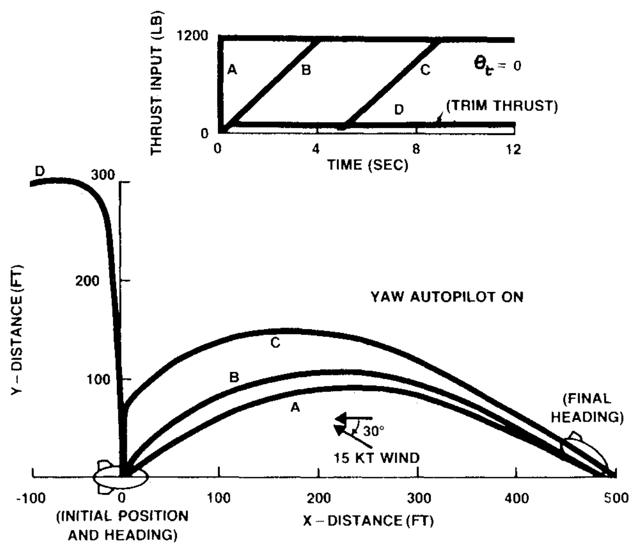

Fig. 16 Thrust rate and lag effects on airship response to a wind shift.

It is quite clear from the simulated flights of the airship that it is highly sensitive to prevailing winds, however light. Consequently, it is believed that the pilot should be provided with a wind vector monitor capable of continually measuring and displaying the average wind magnitude and its direction in the vicinity of the vehicle. With such information it is expected that the operator will be better prepared to respond to wind disturbances during the ground handling.

Both altitude and heading autopilots were found to be helpful in simulating the desired flight conditions of the airship. Although the former was designed to command thrust magnitude or elevator deflection in the simulation, both could be commanded simultaneously with prescribed authorities. Also, the thrust tilt angles could be commanded by such an autopilot instead of thrust magnitude. These possibilities deserve to be explored before designing an actual autopilot for a specific airship. Similarly, simulation results suggest that a heading autopilot would significantly assist a pilot in responding to wind shifts or in achieving a desired azimuthal orientation during ground handling. Quantitative evaluation of these automatic flight control systems in a flight simulator would only confirm their potential benefits.

Concluding Remarks

The advantages of using vectored thrust during V/STOL flight modes of an airship have been successfully demonstrated through vehicle flight simulation. A significant benefit appears to be in widening the range of operational heaviness without additional ground clearance requirements. Unrestricted tail clearance during takeoff and low-speed approach and descent during landing are the other favorable results. Large angles of attack and aerodynamic interference effects associated with steep climb or descent need to be investigated further to ensure efficient performance and overall vehicle structural integrity. It has been shown herein that conventional aerodynamic controls could be favorably integrated with powered thrust/lift vector controls to improve vehicle performance. In this regard, piloted simulations would be more valuable for developing operational procedures and automatic flight control systems. Prevailing winds have been found to be useful in some operational conditions since they tend to activate aerodynamic controls. However, the uncertainty associated with these winds should be noted in developing corresponding piloting techniques.

It was shown that vehicle excursions due to ground-level wind disturbances could be minimized by judicious use of operator time lag coordinated with vehicle turn rate. Specifically, thrust lag and thrust rate have been used herein to indirectly control vehicle heading and sideslip angles. The same effect, to some extent, could be directly generated[10] by asymmetrical application of the twin thrustors to produce both longitudinal control force and yaw control moment. However, significant directional control power at low speeds can be achieved[3] only by incorporating a bow or stern thrustor in the airship configuration. Further studies should evaluate the relative merits and effectiveness of these control strategies in a simulator environment before selecting one of them. Also, vehicle attitude excursions in response to thrust inputs should be investigated in this regard to determine the practicality of associated control strategies.

Inclusion of a state-of-the-art wind vector monitor on the pilot's console, an altitude autopilot, and a heading autopilot should be considered in future airship designs.

Acknowledgments

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