Thrust Vector Control of a V/STOL Airship

B L Nagabhushan* and G D Faiss†
Goodyear Aerospace Corporation Akron Ohio

Potential concepts for thrust vector control of a modern airship were investigated using a six degree of freedom flight dynamics simulation. The specific thrust vectors simulated included those from two ducted fans mounted one on either side of the airship car, each having the capability of tilting in pitch and roll to give vertical and lateral thrust for control An auxiliary thruster at the bow or stern of the airship, which augments its directional control, was also considered It has been found that the tiltable ducted fans provide the airship with greater operational flexibility especially during takeoff and landing Thrust vectoring to provide roll control was found to be effective while ground handling The bow/stern thruster was found to give excellent directional control, which significantly improved the airship lateral maneuverability at low speeds Thrust reversibility, thrust application rate, and tilt rate of thrust vectors were found to be important design parameters having considerable effect on airship flying qualities

Nomenclature

$I_{xx\,yy\,zz}$ = moment of inertia about reference body axes system whose origin is at the vehicle center of mass
L = rolling moment ft lb
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 the vehicle trans lational velocity in the x direction of reference body axes ft/s
v = lateral component of the vehicle translational velocity in the y direction of reference body axes ft/s
w = vertical component of the vehicle 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
θ = pitch attitude of the vehicle rad
θ_t = longitudinal tilt angle of thrust vector rad
ϕ = roll attitude of the vehicle rad
ϕ_t = lateral tilt angle of thrust vector rad
ψ = yaw attitude of the vehicle rad

Introduction

ONE of the perennial problems of airships has been their lack of control power especially at low speeds Often this has resulted in difficulty during ground handling and restricted safe operation in the presence of atmospheric disturbances In order to alleviate this shortcoming airship control by thrust vectoring was considered earlier in this century by Forlanini and more recently by Pavlecka [1] During the last few years advanced airship concepts have been studied[2 8] in which thrust vectors are used to augment a vehicle's lift and control capability Significant improvements in airship performance, stability and control have been found[9 20] for point designs of some of these concepts A modern conventional airship with vectorable thrust from two ducted fans has been under development[21] in Britain However no theoretical or flight test data appears to have been collected systematically for this class of airships

In the present case potential concepts for thrust vector control of a modern airship have been investigated by using a six degree of freedom flight dynamics simulation Thrust vectors simulated include those from two ducted fans mounted one on either side of the airship car and capable of tilting in pitch and roll to give forward and lateral thrust for control An auxiliary thruster at the bow or stern of the airship which augments its directional control was also considered Typical flight conditions corresponding to airship V/STOL modes lateral/directional maneuvers and ground handling were simulated to examine the potential benefits to be derived from thrust vector control Subsequently these results have been compared with similar data for a con ventional airship to emphasize the significance of these benefits The following sections consist of a description of a particular modern airship configuration its flight dynamics simulation, and the corresponding vehicle flight and control characteristics investigated

Airship Configuration

The simulated vehicle was basically configured as a V/STOL airship in the class of Goodyear GZ 20 and the Airship Industries SK 500 airships It was assumed to have vectorable ducted fans instead of the fixed axis pusher type propellers used in existing Goodyear blimps These ducted fans were assumed to be mounted one on either side of the airship car (Fig. 1) such that they could be tilted both in pitch and roll to give longitudinal and lateral thrust components for vehicle control The ability to reverse up to 50% of thrust generated by these ducted fans has been assumed in this case An auxiliary thrust vector at the bow or stern which can be tilted in the horizontal plane was considered to augment the directional control of the airship Typically this control would be used together with the airship rudder deflection subject to a specified mixing law In the present simulation the two control inputs were used synchronously with equal authority for the sake of simplicity

Received Sept 18 1983; revision received Feb 1, 1984

*Specialist Engineer Defense Systems Division Associate Fellow AIAA
†Development Engineer Defense Systems Division

In estimating the physical properties of the simulated airship (Table 1) it has been assumed that the ducted fans would be powered by lighter and more powerful engines than the existing GZ 20 airship engines Further it was assumed that composite materials would be extensively used in the car structure, ducted fans, and outrigger supports It has been assumed that the ducts, bow or stern thruster and any additional fuel to be carried internally would be mostly offset by the above improvements Based on preliminary engineering estimates made in this regard, these assumptions appear to be reasonable Accordingly the range of 200 to 800 lb operating heaviness chosen here seems representative of such an airship configuration Comparing the physical properties of this simulated airship with corresponding data[22 23] for SK 500 it is observed that the preliminary estimates in the present case are typically conservative In any event they adequately characterize the airship configuration for illustrating the application of thrust vector control concepts to such a vehicle

Flight Dynamics Simulation

A six DOF flight dynamics simulation of the above airship configuration 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

Complete rigid body motion of the airship was simulated by using general nonlinear equations of motion [24 25] Basically the airship hull was assumed to be a rigid body supporting the ducted fans and auxiliary thrustor units by means of 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 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[26 27] 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[28] from corresponding derivative data Similarly acceleration dependent aerodynamic forces and moments on the airship were estimated[26] 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 [29] 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 250 hp This power level is representative of both GZ 20 and SK 500 airships' 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 + 120 deg (up) to − 60 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

The bow/stern thrustors were also modeled as pure force generators and were assumed to be operationally similar to the ducted fans. In this case the maximum yaw moment available was assumed to be ± 103 000 ft/lb which is equivalent to having a 1000 lb thrustor at the stern with a moment arm of 103 ft Maximum change in this yaw moment was assumed to occur in 10 s which corresponds to reversing the stern thrust from + 1000 to − 1000 lb or tilting the thrust vector by 180 deg

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

Table 1 Estimated physical properties of the airship

Item	Estimate/design value
Airship	
Envelope volume (stretched)	205 270 ft^3
Overall length	192 ft
Maximum diam of envelope	46 ft
Fineness ratio	4 1
Propulsion	
Tiltable ducted fans	
Maximum continuous thrust	1 200 lb
Maximum reverse thrust	50%
Thrust vector tilt rate (nominal)	5 deg/s
Time for maximum thrust change	10 s
Tilt limit with reference to horizontal	120 deg (up)/60 deg (down)
Auxiliary bow/stern thrustor	
Maximum continuous thrust	1 000 lb
Maximum reverse thrust	100%
Time for maximum thrust change	10 s
Gross weight (nominal)	11 200 lb
Static lift (nominal)	11,000 lb
I_{xx}	156 137 slug ft^2
I_{yy}	692 201 slug ft^2
I_{zz}	569 294 slug ft^2

control the vehicle altitude Similarly, longitudinal and lateral position autopilots were used to maintain vehicle ground position 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 syn chronously while tilting forward ($\pm\theta_t$) and laterally ($\pm\phi_t$) to give corresponding control forces The airship elevator and rudder controls were assumed to be activated simultaneously with the corresponding control input For instance the yaw control command was assumed to actuate both the auxiliary thrustor as well as rudder deflection

Vertical/Short Takeoff

The above six DOF flight dynamics simulation of the airship was used to investigate the advantages of thrust vector control during vertical or short takeoff flights for various heaviness conditions The effect of thrust vectoring during a takeoff on the airship trajectory is shown in Fig 2 The corresponding ground run required to clear a 50 ft obstacle was found to decrease sharply with increase in the pitch tilt angle of the thrust vectors Typically vertical takeoff ($\theta_t = 90$ deg) resulted in an initial advantage of high ascent rate but lower airspeed, compared to a short takeoff with shallow thrust vector angles The lower airspeed attained by taking off vertically is due, of course to the broad side drag and ap parent mass effect of the airship However, it was found that the time required to climb 100 ft was of the same order for all thrust vector angles from 0 through 90 deg Consequently a continuous thrust vectoring program in which the vehicle does a vertical takeoff and subsequently goes through transition to cruise is favorable In such a case the thrust vector is initially tilted up 90 deg for vertical takeoff and subsequently tilted forward during transition to attain the desired cruising speed This results in a short or no ground run for liftoff and also high airspeeds at an altitude

Figure 3 shows the vehicle takeoff trajectory for such a variable thrust vector program compared with that of a conventional takeoff. It is observed that the tail clearance required for conventional takeoff prohibits attaining steep climb angles at liftoff Thus the airship in this case has a longer ground run to clear an obstacle as shown This con straint is typically absent in a continuous thrust vectoring program Further, it offers flexibility in reaching a desired altitude or airspeed within a restricted operating zone such as in the vicinity of an airport This may be limited only by the prevailing wind conditions

Vertical/Short Landing

Thrust vectoring was simulated and found to enhance landing operation of an airship both when it is heavy or near equilibrium Since the vertical component of the thrust vector can be typically used to sustain the heaviness of the airship the need for developing aerodynamic lift on the hull during landing is absent Consequently, landing may be performed at very low speeds and also attain only small nose up pitch attitude angles, particularly with a heavy vehicle (Fig 4) This tends to provide greater flexibility for piloting as well, since one can maneuver the airship throughout the landing ap proach/descent phase and attain steep or shallow flight path leading to a touch down Typical thrust vectoring during a heavy landing is shown in Fig 5. The corresponding flight path for conventional landing indicates that higher landing speed and nose up pitch attitude are, in this case, developed by the airship prior to touch down Indeed a significant advantage of vectored thrust landing is the ability to hover over ground even while operating heavy It was found that thrust reversing during landing resulted in better control of the airship descent rate Ability to change the thrust magnitude quickly was also found to have the same effect (Fig 6) For a ducted fan the upper bound of 10 s for maximum thrust change shown here is perhaps more representative than 0 1 s Based on past experience, a time period of 5 s seems realistic in this regard However, in the present case the intention was to examine the sensitivity of aircraft trajectory to thrust application rate over a wide range

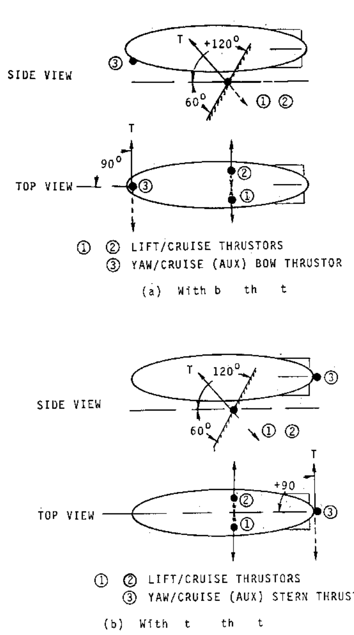

Fig 1 V/STOL airship thrust vector configurations

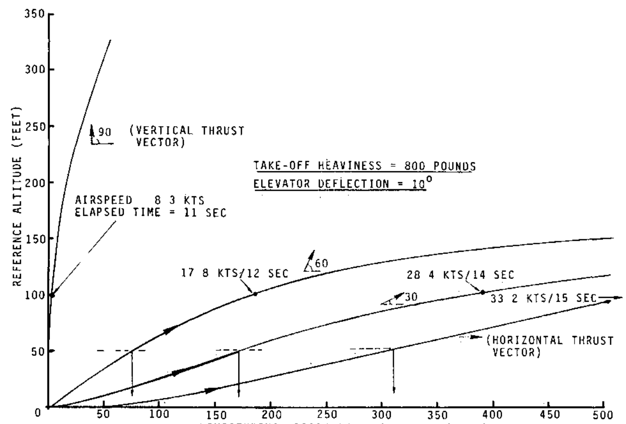

Fig 2 Effect of thrust vectoring on takeoff

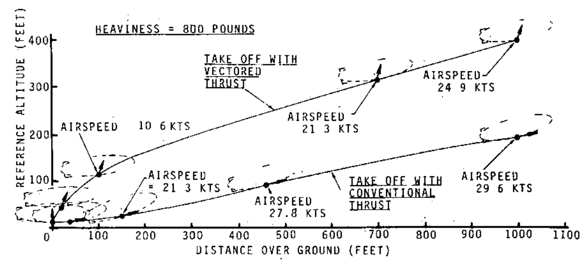

Fig 3 Conventional vs vectored thrust takeoff

Low-Speed Maneuverability

Maneuvering in a horizontal plane was simulated to in vestigate the potential benefits of thrust vectored directional control Basically an auxiliary thrustor was assumed to be located at the bow or stern of the airship such that it could produce control moment in yaw This thrustor was used together with the rudder deflection to provide directional control for the aircraft In order to examine the lateral and directional maneuverability of the vehicle a 180 deg turn around was simulated from a low speed cruising mode while operating at constant forward thrust The conventional airship in such a case was found to slow down to a lower and nearly constant speed during the turn (Fig 7) However using the bow thrustor for directional control in the same flight was found to accelerate the vehicle forward during the turn This also resulted in significantly smaller lateral excursion and shorter time to turn 180 deg than the conventional airship The tendency of the vehicle to accelerate in the latter case is a consequence of smaller sideslip angle and associated lower aerodynamic drag Using stern thrustor in the same maneuver, the airship was found to decelerate during the turn It also resulted in shorter time to turn 180 deg than with the bow thrustor The corresponding lateral excursion was about 50% less in the case of the stern thrustor Airship deceleration observed in this case is a consequence of larger sideslip angle resulting from stern thrust application Based on the above results it appears that a stern thruster for direc tional control would provide greater operational flexibility since it permits maneuvering the airship over a smaller area in a shorter time

Turning

An obvious advantage of having thrust vectored directional control is that turning can be initiated at low speeds[19] (even below 10 knots) when areodynamic control is ineffective This was investigated here by simulating turning at a constant speed A velocity autopilot which commands the thrust vectors of the ducted fans was used to maintain constant flight speed during the turn In such a case it has been found that both bow and stern thrustors significantly reduce the turning radius and time to turn 360 deg compared to con ventional turning with a hard over rudder input (Fig 8) This of course is due to the larger directional control power available in the former case In fact using stern thrustor instead of the bow thrustor resulted in a smaller turning radius This may be understood by again noting that the vehicle configuration with bow thrustor tends to have a smaller sideslip angle in the turn than with the stern thrustor However in both cases constant airspeed was maintained by the velocity autopilot Consequently larger aerodynamic side force is generated on the configuration with stern thrustor which facilitates turning at a shorter radius It was also found that the time to turn 360 deg was nearly the same with bow or stern thrustor This is to be expected since the corresponding directional control power available is also nearly the same Tighter turns at lower speeds were also found to be possible with the stern thrustor Similar results were obtained for the vehicle with heaviness conditions ranging up to 800 lb

Ground Handling

Maintaining ground position upon landing in a gusting or shifting prevailing wind is a difficult task for an airship pilot Consequently thrust vectoring during ground handling was investigated to determine potential advantages over the conventional approach Typically a shifting horizontal wind results in a large drag force acting on the broadside of the airship (Fig 9) which then must be countered to maintain lateral ground position In such a case an adverse roll attitude would also be developed by the vehicle because of the characteristic vertical offset between its aerodynamic center

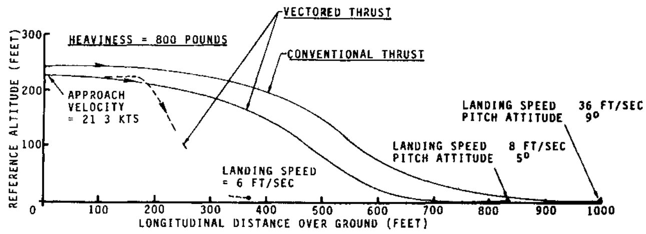

Fig 4 Conventional vs vectored thrust landing

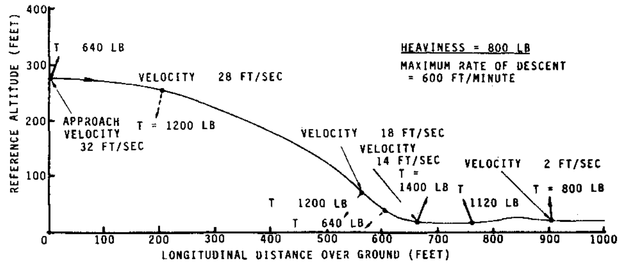

Fig 5 Thrust vectoring during a heavy landing

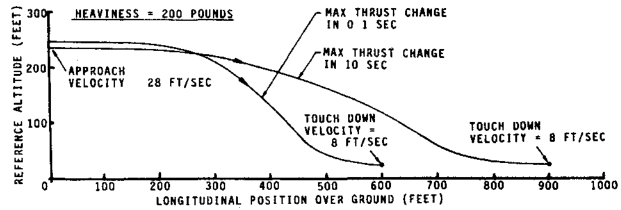

Fig 6 Effect of thrust rate on landing trajectory

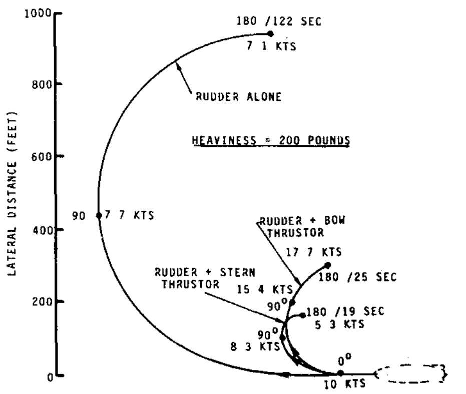

Fig 7 Effect of thrust vector control on vehicle later maneu verability

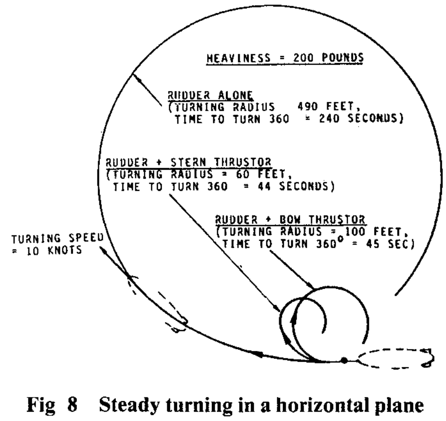

Fig 8 Steady turning in a horizontal plane

and the lateral thrust line Consequently thrust vectoring to maintain the airship lateral position would be effective in wind shifts which did not roll the vehicle beyond the physical limit imposed by ground clearance or otherwise For the example airship the ground clearance limit was set at ±22 deg which corresponds to a cross wind component of 14 knots Equivalently this represents a 45 deg shift for a 20 knot wind in the horizontal plane The corresponding lateral control force required for trim was 1100 lb which was produced by laterally tilting the two ducted fans through 63 deg However in this case the associated structural loadings should be considered in an actual design to ensure overall vehicle in tegrity Response of the airship to a cross wind gust was simulated to determine the suitability of thrust vectoring for lateral or roll control under such conditions Similarly, response of the vehicle to wind shifts was simulated to in vestigate the effectiveness of thrust vectored directional control These are described below with specific examples

Operation in a Cross Wind

Response of the airship to a horizontal 10 knot cross wind gust was simulated while the vehicle was hovering near the ground (Fig 10) Here an altitude autopilot was used to maintain height A lateral autopilot which commanded the lateral tilt of ducted fan thrust vectors, was used to minimize the lateral excursion of the vehicle following the wind input The large excursion in roll observed in this case is due to the cross coupling effect referred to previously while the sub sequent oscillation is characteristic of the airship lateral dynamics [14] The small altitude loss observed is due perhaps to decrease in net vertical thrust component available to sustain vehicle heaviness following the large roll excursion The error in lateral ground position of the airship obtained here is surely less than the corresponding response of a conventional airship having no lateral control at all

Roll Attitude Control

Thrust vectoring which produces a roll control moment on the airship was simulated to investigate the possibilities of controlling the vehicle's roll attitude Basically the thrust vector was tilted laterally to produce a side force which in effect gave a rolling moment about the vehicle aerodynamic center Figure 11 shows the corresponding vehicle response to the 10 knot cross wind considered previously Here the vehicle roll attitude was controlled by a roll autopilot while it was free to move laterally It was found that adequate roll control of the vehicle can be achieved by using a vectored thrust which responds quickly relative to the time period of rolling oscillation of the airship The corresponding tilt rate required for favorable roll response is perhaps beyond that of a gimbaled ducted fan driven mechanically A more effective approach to this type of thrust vectoring may involve deflecting vanes operating in the slipstream of the ducted fans which can effectively tilt the thrust vector relatively quickly In any case the potential for roll control by thrust vectoring is quite clear

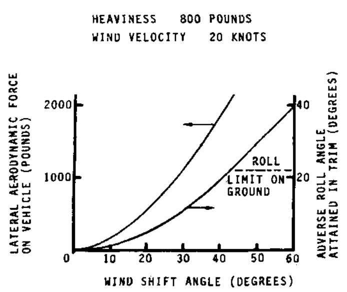

Fig 9 Effect of wind shift on cross wind drag and adverse roll at titude

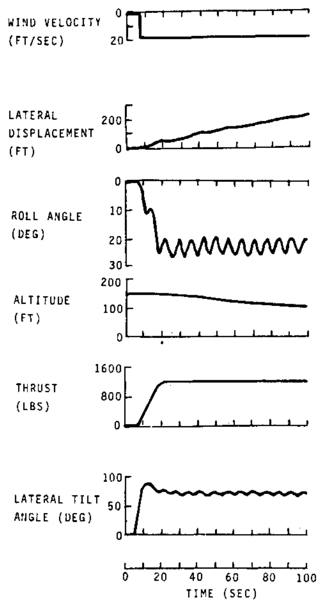

Fig 10 Vehicle response to a 10 knot cross wind gust (lateral autopilot on/roll autopilot off)

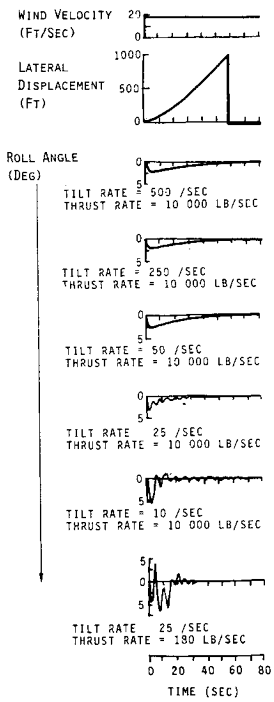

Fig 11 Vehicle response to a 10 knot cross wind (roll autopilot on/lateral autopilot off)

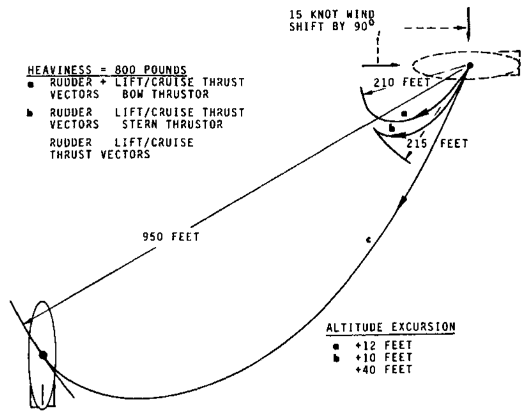

Fig 12 Vehicle response to a 90 deg shift in a prevailing 15 knot head wind

Operation in a Shifting Wind

Subsequent to landing into a prevailing head wind the conventional airship pilot continues to fly the vehicle relative to the wind in order to maintain his ground position Any shift in the wind direction would result in vehicle excursions which the pilot has to counter as he tries to remain stationary over ground Thrust vectoring in such a case was simulated to examine its effectiveness in maintaining vehicle ground position Typical response of the example airship following a 90 deg shift in a prevailing horizontal head wind of 15 knots was simulated The corresponding ground plane trajectory of the vehicle excursion is shown in Fig 12 It was found that by using an auxiliary stern or bow thrustor to augment directional control, the vehicle could be turned into the shifted wind quickly This reduced the airship excursions over the ground significantly compared to the distance covered by using the rudder alone The vertical excursion of the vehicle was also smaller in the former case The lift/cruise thrust vectors in this operation were used to maintain the vehicle longitudinal and vertical positions via autopilots Similar results were also obtained for vehicles with lower heaviness This is to be expected since the thrust vectored directional control power is essentially the same at low speeds and all heaviness conditions.

Concluding Remarks

Thrust vector control concepts for a modern airship which are investigated here, appear to have favorable impact on vehicle flight and control characteristics It has been found that tiltable ducted fans permit V/STOL operation of the airship and provide greater operational flexibility especially with regard to vehicle heaviness Thrust vectored roll control seems to be effective provided the corresponding tilt rate is faster than the vehicle's natural frequency of rolling oscillation Further studies should look into the feasibility of deflecting vanes in the slipstream of the ducted fans which would tilt the fan thrust vector aerodynamically An auxiliary thrustor at the bow or stern of the airship appears to significantly improve directional control of the vehicle particularly at low speeds Consequences of this on vehicle response to wind disturbances during ground handling are indeed favorable The mechanics of providing such a thrust vector by means of a third ducted fan or other devices need to be pursued Thrust reversibility thrust application rate and tilt rate of these thrust vectors have been identified as important design parameters, based on the manner in which they influence vehicle flying qualities examined here The potential significance of thrust vector control during specific operations, such as towing marine systems, should be examined Pertinent control techniques[30,31] based on modern control theory should be investigated in conjunction with the thrust vector control It has been illustrated here that thrust vector control could significantly improve the maneuverability of a conventional airship particularly at low speeds

References

[1] Pavlecka V H Thruster Control for Airships AIAA Paper 79 1595 July 1979

[2] Lancaster J W Semi Buoyant Lifting Body Hybrid Airship Characteristics for Advanced Naval Missions ' AIAA Paper 77 1194 Aug 1977

[3] Lancaster J W ZPG X Design and Performance Characteristics for Advanced Naval Operations AIAA Paper 77 1197 Aug 1977

[4] Brown N D Tri Rotor Coast Guard Airship AIAA Paper 79 1593 July 1979

[5] Nayler A W L , British Lighter Than Air Activity: A Review, AIAA Paper 79 1583 July 1979

[6] Williams, D E The Development of a Heavy Lift Airship AHS Paper 80 9 May 1980

[7] DeLaurier J D McKinnely W D Kung W L Green G M and Sholaert H S B Development of the Magnus Aerospace Corporation s Rotating Sphere Airship AIAA Paper 83 2003 July 1983

[8] Crimmins A G and Doolittle D B The Cyclo Crane: A Hybrid Aircraft Concept AIAA Paper 83 2004 July 1983

[9] Nagabhushan, B L and Tomlinson N P Flight Dynamics Simulation of a Heavy Lift Airship *Journal of Aircraft* Vol 18 Feb 1981, pp 96 102

[10] Nagabhushan B L Jacobs P P Belknap C E and Euler D A Performance Characteristics of a Buoyant Quad Rotor Research Aircraft *Vertica The International Journal of Rotorcraft and Powered Lift Aircraft* Vol 7 No 3 1983 pp 209 223

[11] Tischler, M B Henry R J and Ringland R F , Simulation of Heavy Lift Airship Dynamics over Large Ranges of Incidence and Speed AIAA Paper 81 1335 July 1981

[12] Talbot, P D and Gelhausen P A ' Effect of Buoyancy and Power Design Parameters on Hybrid Airship Performance AIAA Paper 83 1976 July 1983

[13] Curtiss H C and Putnam W F Stability and Control Characteristics of the Aerocrane Hybrid Heavy Lift Vehicle *Journal of Aircraft* Vol 17 Oct 1980 pp 719 726

[14] Nagabhushan B L Dynamic Stability of Buoyant Quad Rotor Aircraft *Journal of Aircraft* Vol 20 March 1983 pp 243 249.

[15] Talbot P D Miura H and Tucker G E Piloted Simulation of a Buoyant Quad Rotor Aircraft AIAA Paper 81 1345 July 1981

[16] Nagabhushan B L Lichty D W and Tomlinson N P Control Characteristics of a Buoyant Quad Rotor Research Aircraft, *Journal of Guidance Control and Dynamics* Vol 6 March April 1983 pp 91 99

[17] Nagabhushan B L and Tomlinson N P Dynamics and Control of a Heavy Lift Airship Hovering in a Turbulent Cross Wind *Journal of Aircraft* Vol 19 Oct 1982 pp 826 830

[18] Lichty D W Control Methods and Hover Capability of Modern Airships AIAA Paper 81 1326 July 1981

[19] Sandlin, D R Flight Test of the HX I Radio Controlled Hybrid Airship AIAA Paper 83 1992, July 1983

[20] Bennett N T and Razavi N Flight Testing and Operational Demonstrations of a Modern Non Rigid Airship AIAA Paper 83 1999 July 1983

[21] Nayler, A W L , LTA Developments in Great Britain AIAA Paper 81 1321 July 1981

[22] *Skyship 500* brochure published by Airship Industries Ltd London England

[23] Velupillai D AD 500: The Commercial Airship *Flight International* Feb 1979 pp 539 544

[24] Strumpf A Equations of Motion of a Submerged Body and Varying Mass Davidson Laboratory Stevens Institute of Technology Rept 771 May 1960

[25] Jones S P and Krausman J A Nonlinear Dynamic Simulation of Tethered Aerostat *Journal of Aircraft* Vol 19 Aug 1982, pp 679 686

[26] ' Preliminary Design of a Hybrid Airship for Flight Research NASA CR 166246, July 1981

[27] Curtiss H C Hazen D C and Putnam, W F LTA Aerodynamic Data Revisited *Journal of Aircraft* Vol 13 Nov 1976, pp 835 844

[28] Bezbatchenko J W Davis R J , and Sowa W W GZ 20 [G/L] Airship Stability and Control ' Goodyear Aerospace Corporation, Akron Ohio, GER 13844 May 1968

[29] McCormick B W , *Aerodynamics Aeronautics and Flight Mechanics* John Wiley New York 1979

[30] Cavalcanti S G Predictive Steering Control of Dirigibles Using the Switching Curve Approach AIAA Paper 81 1327 July 1981

[31] Hookway R O ' A Predictive Steering Control System for Dirigibles *Proceedings of the 10th AFGL Scientific Balloon Symposium* Aug 1978