Control Configuration of a Relaxed Stability Airship

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The control configured vehicle concept of relaxing inherent static stability is applied here to design a modern conventional or V/STOL airship that has fixed or vectorable cruise/lift propulsors and may have auxiliary thrust vector controls for pitch and directional control augmentation. It is shown that conventional control criteria can be met while significantly reducing the required empennage surface area, vehicle aerodynamic drag, and weight by using this design approach. Although they are not a prerequisite for this application, the auxiliary thrust vector controls are found to allow greater reduction in fin size and to have favorable influence on the relaxed stability vehicle performance at low speeds. The results are illustrated here by considering an example airship of 2.8 × 10⁶ ft³.

Nomenclature

AR = aspect ratio
a = aerodynamic lift curve scope, aerodynamic constant, /rad
B = force due to buoyancy, lb
b = tail span, ft, aerodynamic constant
D = aerodynamic drag, lb
i_t = tail incidence angle, deg
K_x, K_y = envelope aerodynamic constants
L = aerodynamic lift, lb; airship length, ft
l_B = bow thruster horizontal location from center of buoyancy, ft
l_s = stern thruster horizontal location from center of buoyancy, ft
M = pitching moment, ft-lb
m = mass of the airship, slug
N = yawing moment, ft-lb
R = radius of turn, ft
r = yaw rate, rad/s
S_c = control surface area, ft^2
S_e = exposed fin area, $= S_c + S_f$, ft^2
S_f = fixed fin surface area, ft^2
S_i = included fin area due to envelope, ft^2
T_B = thrust vector control thrust at bow, lb
$T_{C/L}$ = cruise/lift propulsor thrust, lb
T_s = thrust vector control thrust at stern, lb
V = airspeed of the vehicle, ft/s
$\underline{V}$ = airship envelope volume, ft^3
W = gross weight of the airship, lb
Y = side force, lb
z_c = distance between center of mass and center of buoyancy of the airship, ft
α = angle of attack, deg
β = sideslip angle, deg
γ = flight-path angle, deg
δ_e = elevator control deflection, deg
δ_r = rudder control deflection, deg
θ = airship pitch attitude, deg
θ_t = C/L thrust vector angle, deg
ρ = air density, slug/ft^3
τ = control effectiveness parameter

Subscripts

aero = aerodynamic
bt = ballonet
C/L = cruise/lift propulsor
en = envelope
t = tail
TVC = thrust vector control

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Introduction

RECENT developments in control technology based on digital computers and fly-by-wire or fiber optic systems have made it realistic to consider new criteria and methods in airship design. One of the many control configured vehicle (CCV) concepts called the relaxed static stability (RSS) approach seems particularly attractive and is applied here. In an airship designed with this philosophy, the inherent longitudinal and directional stability need not be built into the airframe if sufficient control power exists to provide artificial stability. The advantage of this approach is that it significantly reduces the size of the empennage and consequently results in a reduction in weight and drag of the vehicle. A reduction in these characteristics will yield an airship with improved performance over one designed conventionally. However, the RSS airship would be more difficult to fly manually and, hence, require state-of-the-art stability augmentation systems.

In the present analysis, a typical modern airship that has V/STOL capability, but not necessarily precession hover capability, is considered for illustrating the RSS design. Since the flying qualities criteria for this type of airship are under evolution, the control requirements have been assumed here to be the same as in the conventional designs of the past, except during V/STOL flight modes. Consequently, the conventional longitudinal, lateral/directional control requirements are used to size the empennage surfaces while assuming the corresponding stability requirements can be met artificially by augmentation systems. The impact of vectoring the cruise/lift propulsors and the use of auxiliary thrust vectored pitch and yaw controls on the airship aerodynamic control power needs is investigated to bring out design trades in control configuration of future airships. In this regard, the effects of varying fin design parameters on airship control parameters and control requirements are illustrated here. Also, the potential for redesigning the conventional airship fins and improving vehicle performance is discussed.

Baseline Airship Description

A modern airship configuration that has an inverted Y-empennage configuration and car-mounted vectorable twin cruise propulsors was used as a design baseline. The cruise/lift (C/L)

Table 1 Estimated physical properties of the example airship

Item	Description/value
Airship	
Envelope volume, stretched, ft^3	2.8×10^6 (nominal)
Overall length, ft	460
Gross weight, lb	147,560
Empennage	
Configuration	Inverted Y
Span, ft	126
Control surface area, ft^2	625 (nominal)
Fixed fin area, ft^2	1660 (nominal)
Effective fin area due to envelope, ft^2	2800 (nominal)
Total fin surface area, ft^2	5085 (nominal)
Aspect ratio (nominal)	1.56
Propulsion/control	
Vectorable cruise/lift propulsors	2 units
Nominal C/L thrust per unit, lb	6000
Auxiliary TVC controls at bow and/or stern	Pitch/yaw axis 1-4 units
Maximum TVC thrust, lb	1000
Reverse thrust	100%

Table 2 Relaxed static stability design effect on aerodynamic stability and control parameters

	Nominal fin area conventional design, $S_c/S_e = 0.27$	50% reduced fin area RSS design, $S_c/S_e = 0.5$
b	126 ft	126 ft
S_c	625 ft^2	571 ft^2
S_t (per fin)	5085 ft^2	3942 ft^2
AR	1.56	2.01
a	2.05/rad	2.59/rad
τ	0.56	0.74
C_{m_α}	0.720	0.731
$C_{m_{\delta_e}}$	−0.288	−0.239
C_{n_β}	−0.856	−0.865
$C_{n_{\delta_r}}$	−0.259	−0.215

thrusters were assumed to be tiltable up or down in the longitudinal vertical plane. The airship envelope configuration was assumed to allow mounting of auxiliary thrusters, which can provide reversible thrust of up to 1000 lb each, at the bow and/or stern of the ship. It should be noted that the RSS design itself is not contingent upon having these auxiliary thrusters. However, they can be effectively used[1] to augment the pitch and yaw control at low airspeeds, as illustrated subsequently. The estimated physical properties of this airship are given in Table 1.

Longitudinal Control Configuration

Conventional aerodynamic design of past airships emphasized the need to provide adequate maneuverability using elevator control, manually operated through a simple aeromechanical system. The stabilizer area was designed to provide inherent, marginal static instability or negative pitch stiffness of the overall vehicle, which improved its vertical plane maneuverability. Typically, the elevator control surface area was sized on the basis of the criterion that the ship in equilibrium, flying at 25 kt, was capable of attaining zero pitch attitude after being trimmed down 6 deg by shifting ballonet air.

Application of the RSS concept to the present case essentially calls for ignoring the stabilizer requirement and considering the control power need alone. Consequently, attention has been paid to improve elevator effectiveness through appropriate fin sizing. Basically, the exposed area of the three fins was reduced, and the proportion of the ruddevator area to that of the total exposed fin area was increased. The effect of these changes on the longitudinal stability and control parameters of the example airship are shown in Table 2. The associated methods[2,3] of evaluation used here are similar to those for a conventional airplane.

It is observed that a 50% reduction in fin size corresponds to a decrease in each fin area by 1140 ft^2 and individual fin weight by 1100 lb. The smaller fins tend to decrease the vehicle pitch stiffness C_{m_α} by 7% and also lower its elevator control power $C_{m_{\delta_e}}$ by 16%. However, these deficiencies are small and could be compensated if necessary by operating at an airspeed 9% higher, by increasing elevator deflection by 19%, or by increasing the tail moment arm by 18%. Although operating at a higher airspeed may be possible, pitch control at very low airspeeds (<20 kt) would be essential to some of the typical airship missions. Consequently, pitch control augmentation at low airspeeds should drive the design criteria in such a case.

Elevator Control in Landing

Using the conventional elevator sizing criterion stated earlier and airship trim equations for pitch plane (see the Appendix), the elevator deflection required to cause 6-deg nose uptrim or downtrim at 25-kt speed has been determined (Fig. 1) for a varying fraction of the nominal fin. Incidentally, holding the downtrim requires greater elevator deflection than uptrim because of the nose-up thrust moment. Assuming elevator deflection to be limited to ± 15 deg, the minimum fin size needed for trim is found to be 70% of the nominal size. If the elevator surface area is assumed to be half the fin area (S_e/S_t = 0.5), then the corresponding minimum fin size for the same trim has been found to be 48% of nominal size (Fig. 2). This can be understood by noting that a larger fraction of the elevator area results in greater effectiveness of that control (larger τ). Also, the smaller fin size, which lowers the already negative pitch stiffness, reduces the elevator deflection required for attaining a given pitch trim. Accomplishing the same pitch trim at a lower speed of 20 kt is possible (Fig. 3) but would require 90% of the nominal fin size. Consequently, the speed at which the elevator criterion is to be satisfied is a critical specification in future designs.

Elevator Control in Heavy Descent

In conventional design, elevator requirement during descent and landing while operating heavy was not considered to be critical. In such a case, the required airspeed was large enough that the elevator deflection was not limiting. In the present case, typical heavy descent flight is examined to determine the impact of reduced fin size on the vehicle's control during descent. The example airship was assumed to be 10,000 lb heavy and descending at 35-kt airspeed and trimmed at a typical − 5-deg flight-path angle. The C/L thrusters were assumed to be horizontal or in conventional configuration.

The corresponding angle of attack was held at 6 deg, which compromised the associated aerodynamic lift and drag. Assuming a ± 15-deg limit on the elevator deflection, the corresponding minimum fin area required for trim (Fig. 4) was found to be 68% of nominal size. If descent was performed at a slightly higher speed of 40 kt (typical of this size airship in the past), then the required minimum fin size was found to be 48% of the nominal.

A heavy descent condition that may occur, for instance, following an aborted takeoff was also analyzed,[4] assuming C/L thrust vectoring was available. The operational constraints, such as field length, were assumed to be such that a descent had to be performed at the same speed of 25 kt as when operating at equilibrium. The corresponding elevator deflection required for a 10,000-lb heaviness of the example airship is shown in Fig. 5, when the C/L propulsors were vectored up. It was found that, at large thrust tilt angles (>70 deg), marginal increments in thrust vector angle can significantly lower the elevator deflection required to hold a trim angle of attack of 6 deg. Basically, in this situation, the C/L propulsors support a greater share of the vehicle heaviness than the aerodynamic lift on the envelope and empennage. It is observed that the 6.4-deg excess in elevator deflection over the 15-deg limit for the 50% fin size can be compensated by increasing the operating C/L thrust magnitude by 1250 lb and vector angle by 1.2 deg. This illustrates the sensitivity of the C/L thruster while operating heavy at low speeds. In fact, this flight condition seems appropriate for sizing the C/L thrust vectoring capability in conjunction with a chosen elevator size in future airship designs.

This analysis indicates that the example airship with a 50% smaller fin area would have adequate elevator control based on conventional design criteria as well as the other operating conditions considered here. The empennage design modification required in such a case would result in control surfaces that have half of the exposed fin areas. Note that essentially the exposed fin is decreased by 50%, whereas the control surface or ruddevator area would remain about the same size as in the conventionally designed empennage (Table 2).

Lateral/Directional Control Configuration

Conventional aerodynamic design of airship empennage for directional stability and control is similar to that for longitudinal stability and control. Typically, the vertical fin or stabilizer area was sized to provide marginal, directional static instability, which enhanced vehicle lateral maneuverability. The rudder control surface area was designed to be able to turn the airship steadily at a minimum radius of 2–3 ship lengths with hard-over rudder.

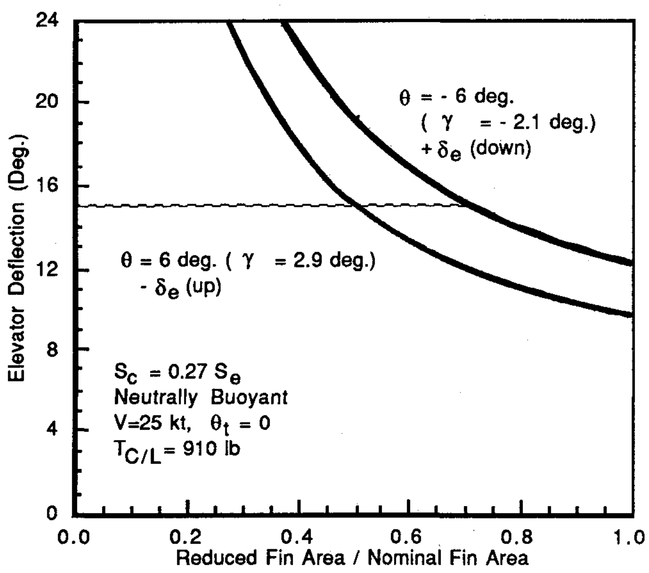

Fig. 1 Elevator deflection required for pitch trim.

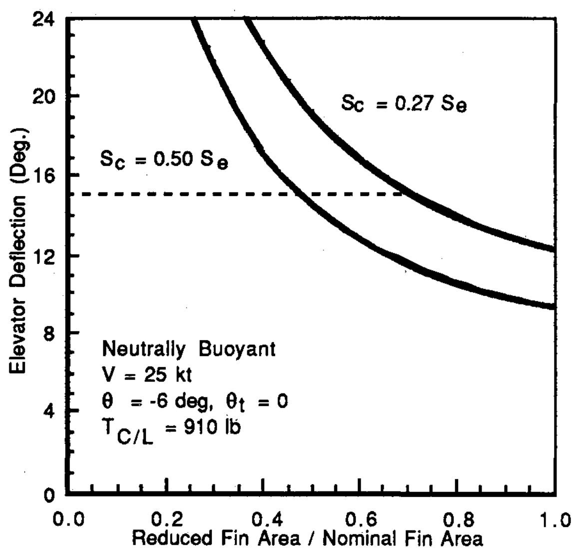

Fig. 2 Fin configuration effect on elevator deflection.

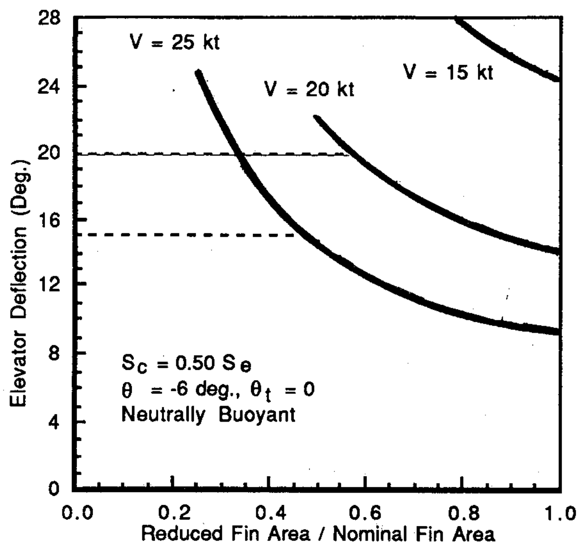

Fig. 3 Flight speed effect on RSS tail size.

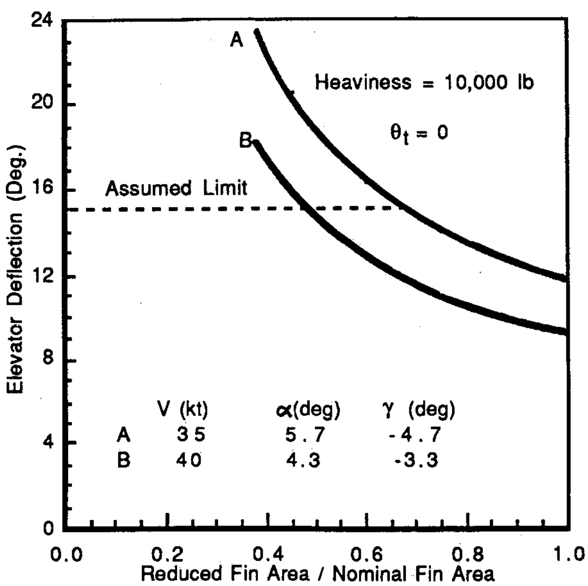

Fig. 4 Flight speed effect on elevator requirement in heavy descent.

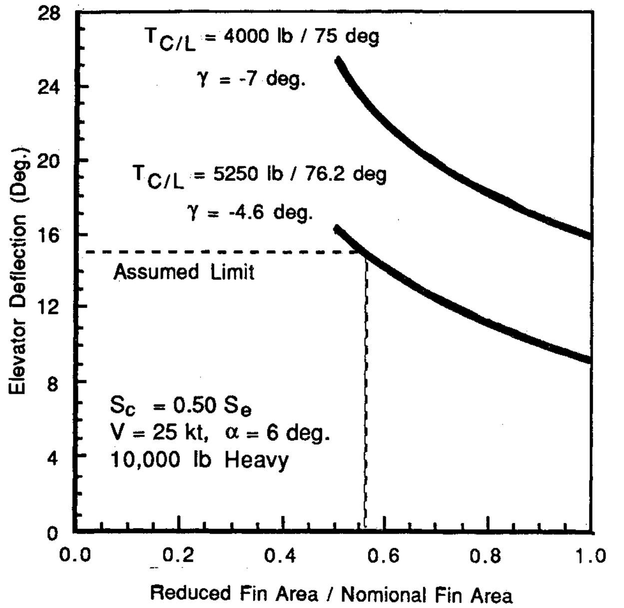

Fig. 5 ***C/L*** **propulsor vectoring effect on elevator control requirement in heavy descent.**

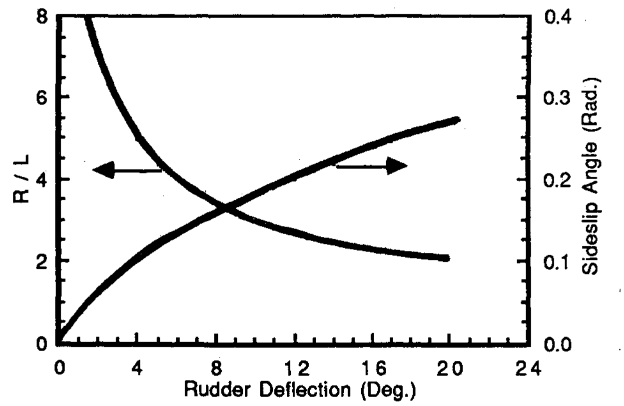

Fig. 6 Turning performance of example airship.

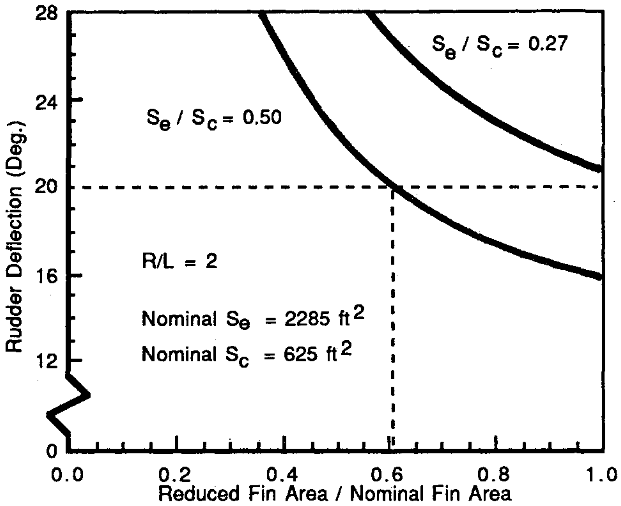

Fig. 7 Fin surface configuration effect on rudder deflection.

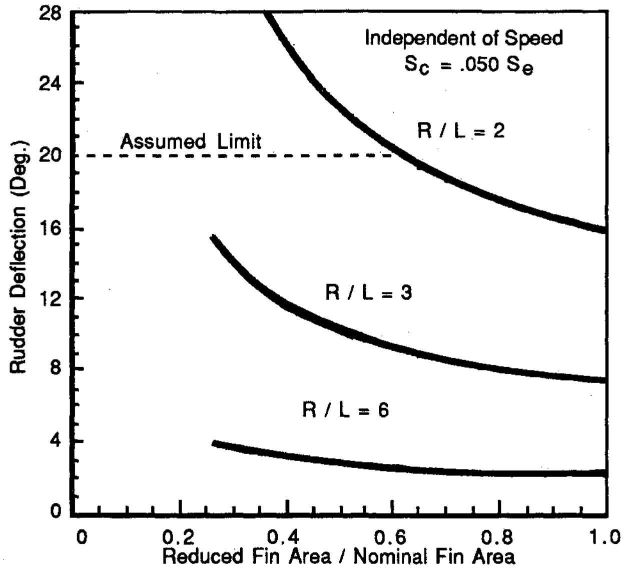

Fig. 8 Turning radius effect on rudder deflection.

In the present case, the RSS concept of relaxing directional static stability while meeting the corresponding control requirements alone is addressed. Consequently, for the baseline design, the fin areas were reduced while increasing rudder effectiveness, similar to that for elevator control discussed earlier. The corresponding directional stability and control parameters were computed and are shown in Table 2. It is observed that a 50% reduction in fin size tends to lower the corresponding vehicle yaw stiffness by 5% and decreases the rudder control power by 16%. However, these deficiencies could be compensated by operating at a 9% higher airspeed, as discussed earlier in sizing elevator control. If it is intended to provide low-speed directional control through auxiliary powered thrust/lift devices, then no compensation would be necessary. Indeed, the aerodynamic controls are less effective at lower airspeeds and should be augmented for significant improvement[1] in lateral maneuverability. However, for the present, no auxiliary thruster controls will be included.

In meeting the conventional directional control criteria stated earlier, rudder control available with a 50% smaller fin was used to evaluate the minimum radius that the airship can be turned at for the following operating condition. A typical rudder deflection of 17 deg was found to cause the vehicle to sideslip at 13 deg. The corresponding radius of turn for the baseline design was evaluated to be 2.1 ship lengths (Fig. 6). These results were obtained by using the lateral/directional trim equations given in the Appendix. The effect of reducing fin area on the rudder requirement for a turning radius of 2 ship lengths ($R/L = 2$) is illustrated in Fig. 7. As shown, assuming a rudder deflection limit of ± 20 deg, a 40% reduced and modified ($S_c/S_e = 0.5$) fin size would be necessary to meet this control requirement. Since the turning radius for an airship is independent of speed, the same rudder deflection would be needed for a given turn at any speed. Figure 8 shows the effect of fin size reduction on the corresponding rudder deflection required for performing a given turn. Significant increase in rudder deflection, needed to compensate for smaller fin size at shorter turn radius, is primarily due to the nonlinearity of the sideslip angle occurring at larger rudder deflections.

Based on this analysis, it is observed that a 40% reduced fin size, having a control surface that is half of the exposed fin area, would be adequate for meeting the conventional directional control criteria.

Auxiliary Pitch/Yaw Control Configuration

It is well known that conventionally designed airships lack adequate pitch and directional control power in many missions, such as towing, refueling, and hovering at sea, which require low operational speeds (5–15 kt), irrespective of prevailing winds or calm air. Consequently, in the present RSS airship design example, it is of interest to consider augmenting the conventional aerodynamic controls with auxiliary powered lift or thrust controls to sustain vehicle control at low airspeeds. Typically, the aerodynamic controls tend to become ineffective at airspeeds below 10 kt. Therefore, this limiting condition is used as a design baseline to illustrate the impact of auxiliary low-speed controls on RSS airship design.

Directional Control

For the example baseline airship with conventional inverted Y fins, the yaw control moment at an airspeed of 10 kt, using nominal rudder deflection of 20 deg, has been estimated to be 99,234 ft/lb. Equivalently, the same control moment can be generated by a lateral stern thrust of 431 lb at a nominal moment arm of 230 ft. Also, a lateral bow thrust of 473 lb at 210 ft would yield the same control moment. If both stern and bow thrusts are used, then the corresponding thrust required from each source has been evaluated to be 225 lb (Table 3). It is important to note that this control power would be available even at zero airspeed, in effect having the same aerodynamic controls as at 10 kt. Similar equivalencies are also illustrated in Table 3 for the pitch control axis. The effect of varying directional thrust vector control (TVC) levels, at various airspeeds, on the rudder requirement for a steady turn at $R/L = 2$ is illustrated in Fig. 9 for reduced fin sizes. It is observed from here that the use of modest TVC levels significantly decreases rudder deflections at lower speeds even for a 40% reduced fin size. Assuming that a normal TVC thrust level of 550 lb, equivalent to conventionally designed maximum rudder power at 15-kt speed, is available at all speeds, the following is shown in Fig. 10. A reduced fin size of 60% would need only 13 deg for rudder deflection with TVC on to turn at a radius of 2 ship lengths. However, the same turn with hard-over rudder at 20 deg and using the TVC could be performed with a 70% reduced fin at speeds up to 30 kt. Also, in such a case, the minimum radius of turn at speeds greater than 30 kt would be greater than 2 ship lengths due to less yaw control moment than with a 40% reduced fin. But this is not likely to be a critical factor since, typically, tighter turns are demanded in low-speed environments rather than at high speeds. Consequently, a directional TVC could be used to further reduce the fin size needed to meet conventional directional control criteria, or else it simply can be used to augment directional control power at low airspeeds to meet specific mission requirements.

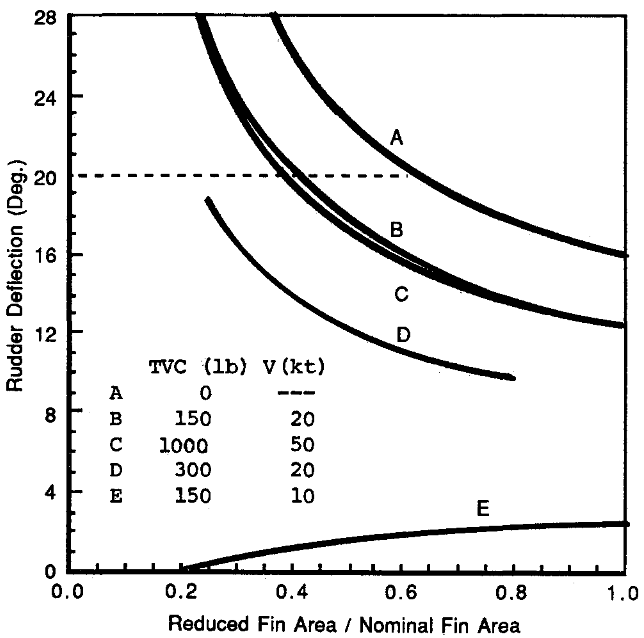

Fig. 9 Effect of directional TVC augmentation on rudder deflection in a turn.

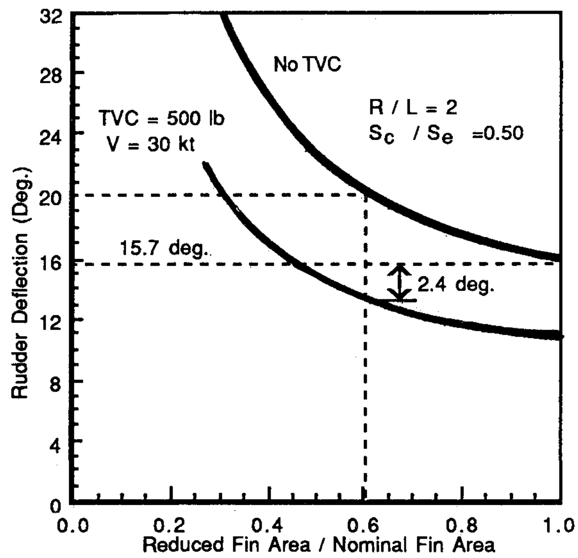

Fig. 10 Directional TVC effect on fin size reduction.

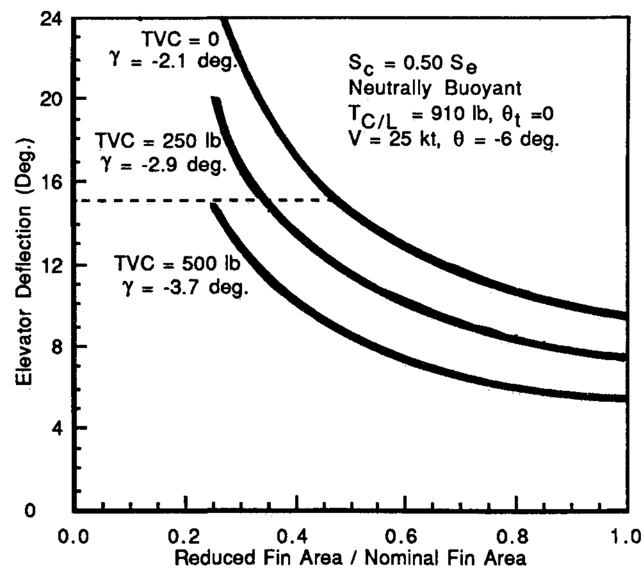

Fig. 11 Pitch TVC effect on fin size reduction.

Table 3 Equivalent aerodynamic and powered lift/thrust controls

Control axis	Airspeed, kt	Aerodynamic control moment[a], ft-lb	Equivalent stern thrust, lb	Equivalent bow thrust, lb	Equivalent stern and bow thrust, lb
Yaw	10	99,234	431	473	225
	20	396,936	1724	1392	902
Pitch	10	109,854	478	523	250
	20	439,416	1910	2092	998

[a]Corresponds to control surface deflection of 20 deg.

Pitch Control

Similarly, the effects of using pitch TVC on the elevator deflection required for meeting the conventional pitch trim criteria are illustrated in Fig. 11. In this case, also, it is found that a nominal TVC thrust of 500 lb applied with a maximum allowable elevator deflection of 15 deg would permit further reduction in fin size to 25% instead of to 50% without TVC.

Concluding Remarks

Control configuration of the airship utilizing the concept of relaxed static stability has been found to have a favorable impact on the overall airship design. It was shown that conventional turning criteria can be met at all speeds with a reconfigured empennage having 40% smaller fins than those conventionally designed, and each fin having a control surface that is 50% of the exposed area. Similarly, conventional pitch trim criteria based on landing at equilibrium have been met with a reconfigured empennage having 50% smaller fins than used in conventionally designed airships. The benefits of having 50% smaller fins are estimated to be 10% reduction in vehicle aerodynamic drag and 45% reduction in empennage weight, which can be traded for additional payload or fuel. This is, indeed, significant for an airship in the class of the example vehicle illustrated here because the 50% reduction in empennage area translates into a 3400-lb weight reduction.

An increment in airship weight due to those of the control surface actuators and hardware associated with stability augmentation by automatic control of the RSS airship is expected. However, the present study has shown that the savings in empennage weight resulting from the RSS design approach is very significant and, hence, this should not be a deterrent. Present trends toward lightweight structural and control system components combined with innovative structural design of the airship empennage, perhaps as a semirigid component, would alleviate this concern even more.

Reconfiguration of the empennage surfaces by permitting the control effectiveness to increase, as done here, is certainly not unique. Other similar design approaches that will allow one to retain the same or better control power as the conventionally designed control surfaces should be investigated. The small decrease in pitch and yaw stiffnesses from their nominal negative values estimated in the present RSS design approach will contribute to greater maneuverability of the vehicle. Obviously, this would be at the expense of making the airship more unstable statically and requiring use of stability augmentation systems. Since the future airship designs would utilize the prevailing state of the art in aircraft technology, this should not be a serious penalty to attaining desired flying qualities. Further investigations in this area are indeed called for.

Pitch and directional control augmentation at low speeds with auxiliary TVCs seems to favorably influence the RSS design. In fact, it was shown that further reduction in fin sizes can be accomplished by utilizing these devices if necessary. However, they are not a prerequisite for control configuration of an RSS airship.

Vectorable cruise/lift thrusters have been found to have significant influence on fin size and elevator control requirement in heavy descent and landing. New criteria that will establish the range of thrust vectoring angles in the pitch plane while utilizing any available pitch control from the elevator need to be evolved. Based on the present analysis, it is suggested that heavy descent following aborted takeoff should be considered as a critical design condition before establishing thrust vector limits in uptilt.

Appendix: Airship Trim Equations

The longitudinal trim of the airship in the pitch plane were determined from the following steady-state equations:

$$T_{C/L}\cos(\theta_t + \alpha) - D - (W - B)\sin\gamma = 0$$

$$T_{C/L}\sin(\theta_t + \alpha) + L - (W - B)\cos\gamma = 0$$

$$M_{\text{aero}} + M_{C/L} + M_{\text{TVC}} + M_{bt} - Wz_C\sin\theta = 0$$

where

$$L = \tfrac{1}{2}\rho V^2 \bar{V}^{2/3}\{[(C_{L_\alpha})_t + (C_{L_\alpha})_{\text{en}}]\alpha + C_{L_{\delta_e}}\delta_e\}$$

$$D = \tfrac{1}{2}\rho V^2 \bar{V}^{2/3}(C_{D_0} + KC_L^2)$$

$$M_{\text{aero}} = \tfrac{1}{2}\rho V^2 \bar{V}\{[(C_{m_\alpha})_{\text{en}} + (C_{m_\alpha})_{\text{car}}]\alpha + C_{m_{\delta_e}}\delta_e + (C_{m_\alpha})_t(\alpha + i_t)\}$$

$$M_{C/L} = T_{C/L}\cos\theta_t\, z_t$$

$$\gamma = \theta - \alpha$$

These equations were solved typically to obtain the required α, δ_e, and $T_{C/L}$ for a specified γ, V, and θ_t. The other variables in these equations were essentially treated as given parameters.

The lateral/directional trim of the airship in the yaw plane was determined from the following steady-state equations:

$$Y_{\text{TVC}} + Y_{\text{aero}} = mVr\,(1 + K_x\cos^2\beta + K_y\sin^2\beta)$$

$$N_{\text{TVC}} + N_{\text{aero}} = 0$$

where

$$r = V/R$$

$$Y_{\text{TVC}} = (T_s - T_B)\cos\beta$$

$$Y_{\text{aero}} = \tfrac{1}{2}\rho V^2 \bar{V}^{2/3}[C_{y_\beta}\beta + C_{y_r}(a + b\,|\beta|)r + C_{y_{\delta_r}}\delta_r]$$

$$N_{\text{TVC}} = (T_B l_B + T_S l_S)$$

$$N_{\text{aero}} = \tfrac{1}{2}\rho V^2 \bar{V}[C_{n_\beta}\beta + C_{n_r}(a + b\,|\beta|) + C_{n_{\delta_r}}\delta_r]$$

These equations were solved typically to obtain the turn radius R/L and sideslip angles for a specified rudder deflection and directional TVC thrust input. It can be observed from these equations that, in the absence of any TVC augmentation, the turning motion of the airship is independent of flight speed.

Acknowledgments

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