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Pitch Handling Qualities Investigation of the Tailless Gull-Wing Configuration

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A handling quality analysis of the tailless swept gull-wing configuration is presented here. This aircraft configuration is defined, for the purpose of this discussion, as one having multiple sweep and dihedral angles. The effects of changes in the static margin and of gusts on handling qualities were investigated for this new configuration. The Exulans, an aircraft currently under development, was used as a representative example of a tailless swept gull-wing configuration. The Exulans uses variable outboard wing sweep as a means of static margin control. This is achieved by a sweep hinge located at semispan. The pilot can change the outboard wing sweep angle for purposes of pitch trim. The Exulans is a research test bed that is being used to investigate the possibility of designing a tailless aircraft with both good handling qualities and a high Oswald efficiency. The handling qualities investigation was limited to the longitudinal plane. A Neal–Smith handling quality analysis was used to investigate handling qualities at different static margins, and a Mönnich–Dalldorff analysis was used to investigate gust handling qualities. Time domain simulations were also used to investigate the aircraft gust response. It is shown that the gull-wing configuration promises to have satisfactory handling qualities for a region of center of gravity locations, for which good Oswald efficiency can also be achieved. A satisfactory gust response can also be achieved.

Nomenclature

C_{De} = equilibrium drag coefficient
$C_{L\alpha}$ = lift coefficient curve slope, 1/rad
$C_{L\delta e}$ = lift coefficient due to elevator deflection, 1/rad
C_{Mq} = pitching moment coefficient of aircraft due to pitch rate or pitch damping, 1/rad
$C_{M\alpha}$ = pitching moment coefficient curve slope of the aircraft, 1/rad
$C_{M\delta e}$ = pitching moment coefficient due to elevator deflection, 1/rad
d = neuromuscular time delay of a pilot
F_s = pitch control stick force, positive for pull, N
g = gravitational acceleration, m/s^2
K_p = steady-state pilot gain
K_θ = "airframe only" gain
L = total aircraft lift, N
m = aircraft mass, kg
n = aircraft load factor $L/(mg)$, or the normal acceleration of aircraft
S = aircraft wing area, m^2
s = Laplace variable, 1/rad
V_T = true airspeed, m/s
x_{cg} = distance from the leading edge of the wing on the aircraft longitudinal axis to the center of gravity of the aircraft
ζ_{sp} = short period mode damping ratio
θ_e = error between the commanded pitch attitude and the aircraft pitch attitude, rad
θ = pitch angle, rad or degrees
ρ = air density, kg/m^3
τ_{p1} = time constant of control system lead element, s
τ_{p2} = time constant of control system lag element, s
$\tau_{\theta 2}$ = numerator time constant (airframe lead time constant) of the elevator deflection to pitch rate transfer function, s
ω_{nsp} = short period mode natural frequency, rad/s

I. Introduction

THE tailless gull-wing configuration is an unconventional layout for aircraft but is found on many fliers in nature. It is defined here as a wing configuration that has both multiple sweep angles as well as dihedral angles without tail wings dedicated for stability or control. The wandering albatross (*Diomedea exulans*) is an example of a bird that has such a wing configuration.

The gull-wing configuration is the focus of a research project [1]. This investigation is intended to include full-scale flight testing. For this purpose, a test aircraft, the Exulans, is being developed. This test bed is designed as a single-seat ultralight glider. Before test flying commences, the anticipated flight properties should be well understood. This research investigates the tradeoff between flight

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efficiency and handling qualities. It looks at various ways in which pitch control and pitch trim can be achieved without adverse effects on efficiency. For this reason, the Exulans incorporates variable wing sweep on the outer wings as a means of static margin (SM) control for pitch trim.

For a new aircraft configuration to be justified, it should be superior in aerodynamic efficiency while having comparable handling qualities. Many other tailless designs such as the SB-13 have shown shortcomings in their handling qualities [2]. Tailless aircraft have low aerodynamic pitch damping and pitch mass moment of inertia when compared to aircraft designs with an empennage. Therefore, tailless aircraft have unique pitch dynamics that may affect the handling characteristics.

Established methods were used to analyze the handling qualities of the gull-wing configuration, using the Exulans as a specific example. The Neal–Smith analysis technique [3] was used to evaluate the pitch handling characteristics of the aircraft in calm atmospheric conditions. This technique was chosen because it uses a pilot model formulation with which the pilot/aircraft interaction may be studied in a repeatable and controlled manner. The Mönnich–Dalldorff [2] criterion was used to evaluate the aircraft handling characteristics in gusty conditions. The handling qualities of the Exulans are also compared to the handling characteristics of an existing tailless and a conventional glider design.

II. Swept Gull-Wing Configuration

The gull-wing configuration is unconventional, and so it can be compared with very few existing designs. Historical examples of aircraft with similar geometry include the Weltensegler [4] and its successor, the Charlotte [1], of Germany and the SZD-6x Nietoperz [5] of Poland.

The Exulans is presented schematically in Fig. 1. The inboard wing portion is swept forward and has dihedral, while the outboard section is swept backward and has anhedral. The outboard section of the wing has controllable variable sweep, which is made possible with a hinge situated halfway between the wing root and the wing tip. The variable sweep of the outboard wings is used to control the longitudinal trim condition. This eliminates the need for deflecting a wing-based control surface, which would adversely impact the spanwise lift distribution. The variable wing sweep allows the lift distribution to remain favorable throughout the operational speed range of the aircraft. Additionally, it has the advantage that the useful range of the control surfaces is not compromised by trimming the aircraft, as is often the case with tailless aircraft that use only the elevons for longitudinal trim control. The outer wing sweep angle could be as high as 36 deg for fast flight and as low as 24 deg for slow flight, depending on the position of the c.g. for a given flight.

The Exulans uses elevons on the outboard sections for pitch and roll control, whereas the inboard portions contain flaps. Controllable winglets are situated on the tips of the outboard sections. These are primarily used for yaw damping and for directional control. The

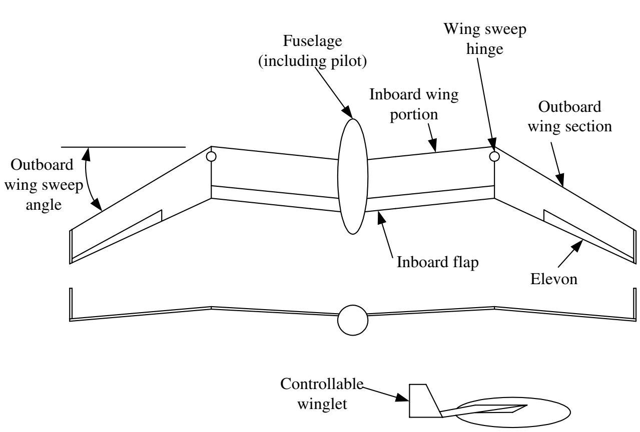

Fig. 1 Schematic of the swept tailless gull-wing configuration (planform view shown here with 30 deg outboard sweep).

winglets can rotate to change their toe-out angles. The winglet toe-out angles are appropriately linked to the sweep angle while yaw control inputs are superimposed.

Like other tailless aircraft, the Exulans has low aerodynamic pitch damping and pitch inertia when compared to tailed aircraft designs.

III. Aerodynamic Efficiency of Tailless Aircraft

The core challenge in tailless aircraft design concerns the tradeoff between aerodynamic efficiency and handling. Therefore, the design objective relating to efficiency will be summarized here. Two special longitudinal c.g. locations are of particular interest. These relate to the E point and the O point.

The E point [4] is defined as the position of the center of pressure of a wing having an elliptical circulation distribution along its span. Such a distribution is required to maximize Oswald efficiency [6], a factor of the induced drag of the aircraft. It is therefore desirable to place the aircraft c.g. on the E point because this would be required to achieve trimmed flight with the optimal circulation distribution.

The O point [4] is comparable to the E point but its definition relates to a wing with winglets. In this case, according to Horstmann [7], the most favorable circulation distribution is elliptical from tip to tip of the winglets. This implies that the wing tips carry more circulation than would be the case without winglets.

On a swept back wing, this would mean that the center of pressure lies further back. Therefore, the O point would lie behind the E point of the same wing without winglets.

The Exulans has winglets, however, their primary function concerns yaw damping and yaw control. If they can additionally improve the effective span, the Oswald efficiency and thus the induced drag would improve. In the ideal case, the winglets would be providing circulation as suggested by Horstmann [7]. Trimmed flight would then require the c.g. to coincide with the O point. If handling qualities allow the associated static margin, then flight with the c.g. at the O point would be possible. If, however, the winglets do not contribute to the effective span, then the best circulation distribution would be comparable to that associated with the E point (as if the aircraft has no winglets). Therefore, the region between the E point and the O point would represent desirable c.g. locations with wing efficiency potentially at its best with the c.g. at the O point. Depending on the outcome of the handling quality study, a designer can select an appropriate winglet toe-out angle and twist to provide the best circulation distribution with the center of pressure perhaps somewhere between the E and the O point.

Another center of pressure location of interest has an indirect implication on efficiency. This is the C point [4], the center of pressure associated with constant local lift coefficients along the span. A wing which would be configured to produce the maximum circulation along the span would have the lowest possible stall speed. Because wing size depends directly on the stall speed requirement, the smallest possible wing would need to be flown with the c.g. in the C point when requiring the lift coefficient to be high. If handling qualities permit, the wing size could be minimized in favor of lower parasitic drag.

The locations of the E, O, and C point, like that of the neutral point, all depend on the wing (and winglet) planform and therefore vary with the outer wing sweep angle. Their locations can be closely approximated via the wing geometry if one assumes that the centers of pressure of the local wing sections are located at the local quarter-chord position. This approximation would be acceptable if the section pitching moment coefficients are small, as would generally be the case for the wing sections used on tailless aircraft wings. The position of the neutral point has to be found by numerical means. In this study, a vortex lattice method was employed [8]. The winglets were included in the numerical model. Also, the c.g. of the aircraft changes with sweep angle because of the mass of the outer wing and the winglet, but at a smaller rate.

The results of the E , O, and C point calculations for the range of sweep angles of the Exulans are presented in Fig. 2. The figure also shows the location of the neutral point for different values of wing sweep. It can be seen that the C point is almost coincident with the neutral point for the whole range of sweep angles. The E point is ahead of the neutral point (or at a positive static margin). The O point is aft of the neutral point for the whole range of sweep angles. Flight with the c.g. in the O point would thus be done with a small negative static margin.

IV. Handling Quality Investigation at Different Static Margins with a Pilot-in-the-Loop Model

The Neal–Smith method [3] was used to evaluate aircraft handling characteristics at different static margins with a mathematical pilot model in the loop. A range of static margins (and thus c.g. locations) has been defined for desirable aerodynamic efficiency. Now the handling qualities have to be evaluated for this range of static margins. This is done to find the most desirable static margins in terms of the handling qualities. This investigation was used to ascertain whether or not a common region exists in which both efficiency and handling qualities are desirable.

A pilot in the loop was required to investigate the effect of a pilot in a controlled and repeatable manner. When the pilot transfer function is cascaded with the airframe transfer function inside a feedback loop, as shown in Fig. 3, the closed-loop transfer function has very different characteristics compared to the airframe model in isolation.

The generic pilot model transfer function used with the Neal–Smith method is presented in Eq. (1):

$$\frac{F_s}{\theta_e} = K_p e^{-ds} \frac{\tau_{p_1} s + 1}{\tau_{p_2} s + 1} \tag{1}$$

The K_p variable in Eq. (1) is the steady-state gain of the controller. In this case, the controller is not an automatic device (such as an autopilot), but the human pilot. In practice, the pilot gain will not be constant over the whole flight, but would vary in different flight conditions based on the pilot's discretion. The variable d is a time delay. This models the reaction time of the pilot. The time delay incorporates the time to sense the need for action, the time to make a decision, as well as the neuromuscular lag of the human body [3]. The value of 0.3 was used for the time delay parameter in the analysis done by Neal and Smith. The same value was used for the study on the Exulans.

The pitch control stick force to pitch attitude transfer function [9] shown in Eq. (2) was used to model the airframe. The airframe transfer function was created by using stability derivatives to calculate the short period natural frequency and short period damping ratio. The stability derivatives for the Exulans were calculated using a vortex lattice method [8]. The stability derivatives were calculated for a range of different sweep angles:

$$\frac{\theta}{F_s} = \frac{K_\theta(\tau_{\theta_2} s + 1)}{s[(s^2/\omega_{\text{nsp}}^2) + (2\zeta_{\text{sp}}/\omega_{\text{nsp}})s + 1]} \tag{2}$$

Equation (3) shows how the airframe gain K_θ of Eq. (2) was calculated [3]:

$$K_\theta = \frac{g}{V_T(F_s/n)_{\text{SS}}} \tag{3}$$

The preferred value of $(F_s/n)_{\text{SS}}$ for the pilots involved with the tests of [3] was between 20 to 31 N/g. The average value of 25.5 N/g was chosen for the analysis of the Exulans.

The Neal–Smith method [3] assumes that the human pilot adjusts his own lead, lag, and gain so as to minimize the droop and peak of the frequency response. This process is modeled mathematically by adjusting the lead and lag time constants in Eq. (1) to optimize the closed-loop frequency response. This is done by minimizing the droop and peak of the system's Bode plot. The maximum lead or lag provided by the "pilot" is then determined from this calculation and plotted on a pilot opinion chart (see Fig. 4) that has been created by flight testing [3]. A standardized pilot opinion rating is then read off

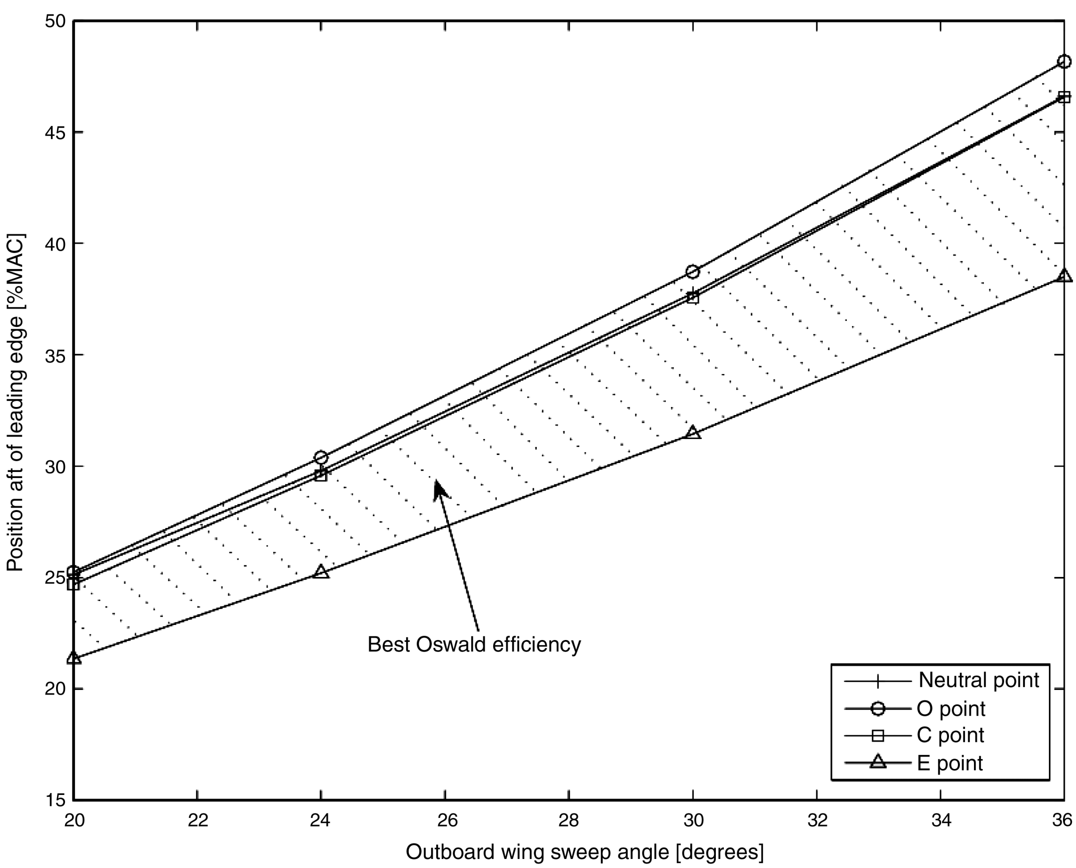

Fig. 2 Positions of the O, E, and C point and neutral point against the wing sweep angle for the Exulans. The region between the E and the O point would represent c.g. locations for best Oswald efficiency depending on the contribution by the winglets to the effective span. The *y* axis represents the distance behind the wing leading edge at the plane of symmetry.

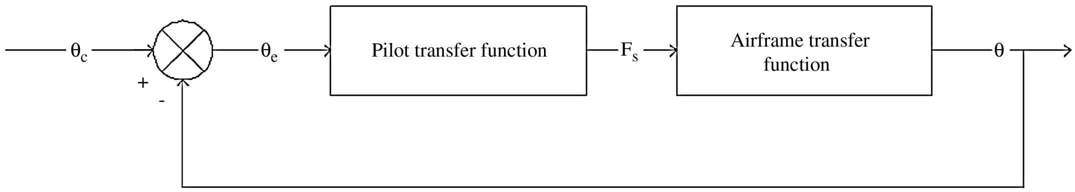

Fig. 3 Control closed-loop diagram of the pilot and airframe.

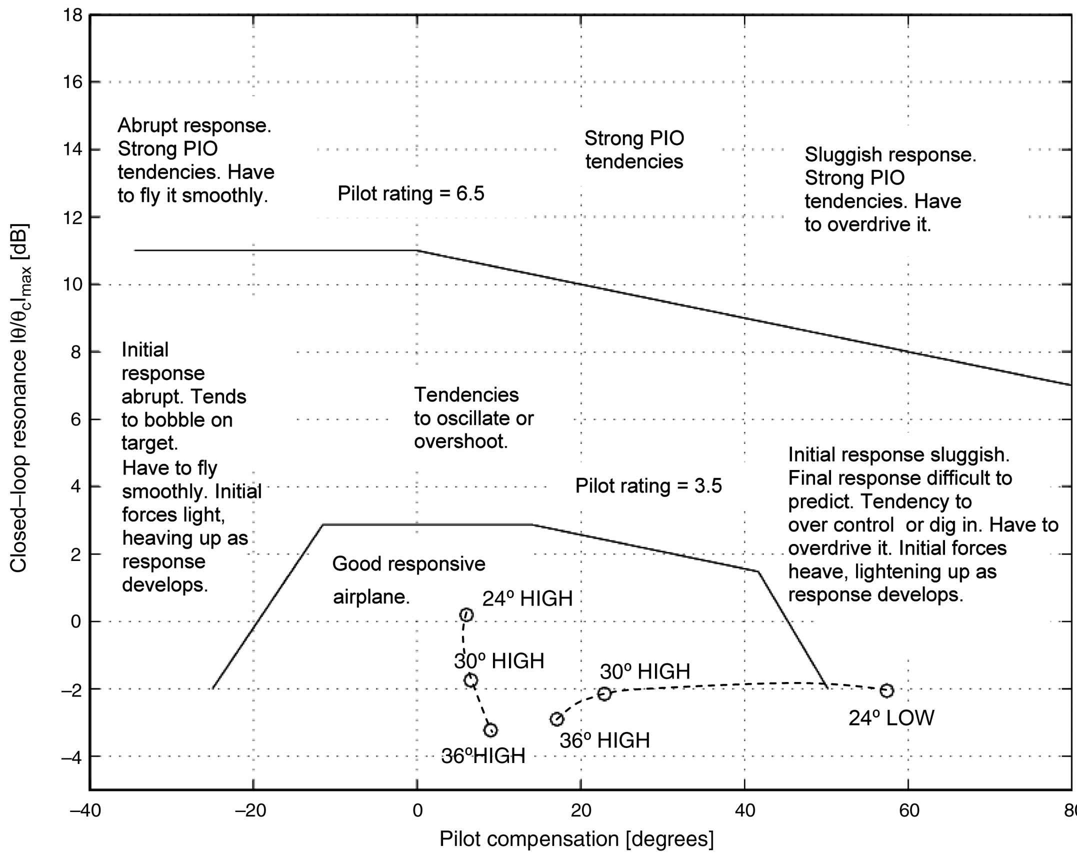

Fig. 4 Plot showing Neal–Smith analysis results [3].

the graph on which the calculated data have been plotted. This pilot rating (PR) is based on the Cooper–Harper pilot rating scale [10]. The phenomenon of pilot-induced oscillation (PIO) occurs when the pilot attempts to damp the pitch rotation of an aircraft, but inadvertently exaggerates that motion. In the context of the Neal–Smith analysis [3], an aircraft is prone to pilot-induced oscillation when the pilot is unable to minimize the closed-loop resonance of the aircraft (see the upper half of Fig. 4).

The Neal–Smith method was applied to different configurations of sweep and static margin of the Exulans. The different configurations are presented in Table 1. The handling qualities were evaluated for low, medium, and high sweep angles. Each sweep angle was evaluated at low and high static margins. Even though the aircraft is statically unstable at negative static margins, it is necessary to investigate whether the combination of the pilot and the aircraft will lead to a total system with acceptable handling qualities.

Table 1 Exulans configurations used in the Neal–Smith handling quality evaluation

Sweep	Static margin classification	Static margin	Static margin reference
24 deg	Very low	−2.8%	2% at 30 deg
24 deg	Low	0.2%	5% at 30 deg
24 deg	High	10.2%	15% at 30 deg
30 deg	Low	5.0%	5% at 30 deg
30 deg	High	15.0%	15% at 30 deg
36 deg	Low	10.3%	5% at 30 deg
36 deg	High	20.2%	15% at 30 deg

Table 1 shows the static margin of the aircraft at the given sweep angle as well as the static margin that the aircraft would have if the wings were swept at 30 deg as a reference. Thirty degrees was chosen as a reference because this is the design cruise sweep angle. The results of the Neal–Smith analysis for the different configurations listed in Table 1 are presented in Fig. 4.

Figure 4 indicates that the Exulans has satisfactory handling characteristics with the pilot in the loop for a wide range of sweep angles and static margins. Handling qualities start to deteriorate with a combination of low sweep angle and low static margin. The lead and lag time constants in Eq. (1) of the configuration having the negative static margin (labeled "very low" in Table 1) could not be adjusted to meet the Neal–Smith criteria and therefore this configuration could not be plotted in Fig. 4. The same was found for other cases of negative static margin. This suggests that the handling qualities of the Exulans become unacceptable with static margins of less than zero. It is noteworthy that the Neal–Smith criteria was only correlated with flight test results until −2 dB. Figure 4 indicates that two configurations fall outside the −2 dB range, but within the acceptable pilot compensation angle. Strictly speaking, the Neal–Smith criteria cannot be applied to these two configurations. The general trend of the flight test data of the Neal–Smith criteria seems to indicate that pilot opinion got better with a lower closed-loop resonance. If this trend is extrapolated, it stands to reason that the configurations with less than 2-dB closed-loop resonance (but within

Table 2 Constants used in the Mönnich–Dalldorfff analysis for the gull-wing configuration

Sweep	C_{Mq}	$C_{L\alpha}$	C_{De}
24 deg	−1.218	5.232	0.040
30 deg	−2.035	5.146	0.019
36 deg	−3.097	5.031	0.016

the acceptable pilot compensation limits) have acceptable handling qualities. This does require flight testing for verification.

V. Handling Quality Investigation for Gusty Atmospheric Conditions

The Mönnich–Dalldorff flying quality criterion [2] for tailless aircraft was used to evaluate the handling qualities of the gull-wing configuration in gusty atmospheric conditions. The method comprises the evaluation of the inequality presented in Eq. (4) for a given aircraft configuration to check whether or not it will have satisfactory handling qualities in gusty conditions. If the inequality is satisfied, the aircraft configuration should have satisfactory handling qualities in gusty conditions.

Satisfaction of the inequality guarantees that the vertical gust velocity to pitch attitude transfer function has a left-plane zero. If this is not the case, the transfer function has a right-plane zero. This also means that the aircraft phase response is nonminimum. The phase of the response could be out of phase with gust inputs by as much as 180 deg. This makes it extremely difficult for the pilot to be able to damp the aircraft response magnitude with elevator/elevon inputs, as the phase shift of the response makes it difficult to judge the direction of the gust disturbance. The result of a right-plane zero from the gust response transfer function is that the pilot will most likely cause pilot-induced oscillations instead of damping the magnitude of the gust response during gusty atmospheric conditions:

$$\frac{C_{M_\alpha}}{C_{M_q}} < (C_{L_\alpha} + C_{D_e}) \frac{\rho S(\mathrm{MAC})}{2m} \tag{4}$$

where MAC is the mean aerodynamic chord.

The magnitudes of the stability derivatives in Eq. (4) were calculated using a vortex lattice method [8]. The Mönnich–Dalldorff analysis [2] was performed at sea level density and 12,000 ft for international standard atmosphere conditions. The analysis was performed for several cases of wing sweep and static margin to investigate the different possible configurations of the Exulans. The static margin is specified by means of the reference static margin at 30 deg as was done in Sec. IV. The 2, 5, 10.7, and 15% at 30 deg sweep reference static margin configurations were analyzed for 24, 30, and 36 deg of outboard wing sweep. The analysis was also performed on the ASW-19 as well as the SB-13 to provide reference analysis results. The ASW-19 is an example of a standard-class tailed glider. The analysis of the ASW-19 is useful for comparative purposes between tailed and tailless gliders. The ASW-19 has good gust handling characteristics at all altitudes according to the Mönnich–Dalldorff analysis [2]. This is in agreement with the general pilot opinion of the aircraft. The SB-13 is also a standard-class glider, but tailless, and has satisfactory handling characteristics in calm atmospheric conditions, but unsatisfactory handling characteristics in a gusty atmosphere according to the Mönnich–Dalldorfff analysis. This analysis is in agreement with the flight tests that were performed on the SB-13 [4].

The results for the different sweep and static margin cases are presented in Tables 2–6. The results of the analysis performed on the ASW-19 and the SB-13 are shown in Table 7. The abbreviations "LH" and "RH" in these tables refer to the left-hand side and the right-hand side of the inequality presented in Eq. (4). Additional data

Table 3 Mönnich–Dalldorfff analysis for 2% static margin configurations at 30 deg sweep configurations

Sweep	$C_{M\alpha}$	LH	RH sea level	Inequality satisfied	RH 12,000 ft	Inequality satisfied
24 deg	0.148	−0.121	0.247	Yes	0.172	Yes
30 deg	−0.103	0.051	0.242	Yes	0.169	Yes
36 deg	−0.365	0.118	0.236	Yes	0.165	Yes

Table 4 Mönnich–Dalldorfff analysis for 5% static margin at 30 deg sweep configurations

Sweep	$C_{M\alpha}$	LH	RH sea level	Inequality satisfied	RH 12,000 ft	Inequality satisfied
24 deg	−0.011	0.008	0.247	Yes	0.172	Yes
30 deg	−0.257	0.117	0.242	Yes	0.169	Yes
36 deg	−0.518	0.157	0.236	Yes	0.165	Yes

Table 5 Mönnich–Dalldorfff analysis for 10.7% static 30 deg sweep configurations

Sweep	$C_{M\alpha}$	LH	RH sea level	Inequality satisfied	RH 12,000 ft	Inequality satisfied
24 deg	−0.309	0.182	0.247	Yes	0.172	No
30 deg	−0.551	0.216	0.242	Yes	0.169	No
36 deg	−0.804	0.217	0.236	Yes	0.165	No

Table 6 Mönnich–Dalldorfff analysis for 15% static 30 deg sweep configurations

Sweep	$C_{M\alpha}$	LH	RH sea level	Inequality satisfied	RH 12,000 ft	Inequality satisfied
24 deg	−0.531	0.268	0.247	No	0.172	No
30 deg	−0.772	0.267	0.242	No	0.169	No
36 deg	−1.018	0.251	0.236	No	0.165	No

Table 7 Mönnich–Dalldorfff analysis for the ASW-19 and the SB-13

$C_{M\alpha}$	C_{Mq}	$C_{L\alpha}$	C_{De}	LH	RH sea level	Inequality satisfied	RH 12,000 ft	Inequality satisfied
					ASW-19			
−0.633	−17.680	5.917	0.013	0.036	0.086	Yes	0.060	Yes
					SB-13			
−0.590	−5.370	5.470	0.010	0.110	0.073	No	0.051	No

Table 8 Additional data for the ASW-19, the SB-13, and the Exulans used for the analysis in the preceding tables

Aircraft	S, m^2	m, kg	MAC, m
ASW-19	11.8	408	0.82
SB-13	11.8	435	0.80
Exulans	12.0	160	1.02

used in the Mönnich–Dalldorf analysis of the ASW-19, the SB-13, and the Exulans are presented in Table 8.

The results show that the Exulans is likely to have satisfactory gust handling qualities at 24, 30, and 36 deg outboard wing sweep at low altitude and low static margin. The Exulans is expected to have degraded handling characteristics in gusty atmospheric conditions at high altitude.

VI. Comparative Gust Response Simulation Results

Time domain simulations were performed to make a qualitative evaluation of the Exulans handling qualities. The aircraft pitch response with respect to a gust input was used to gauge its handling qualities. The simulations were performed using linear aerodynamics, except for the nonlinear drag polar. The equations of motion for small disturbance theory [11] were used in the simulation. The comparative simulations used the results of gust response simulations for three Exulans configurations, as well as simulations with the SB-13 and the ASW-19.

An Exulans configuration with low outboard wing sweep (24 deg sweep angle) and one with high wing sweep (36 deg) were used for the comparative simulation. A cruise configuration (30 deg) was also simulated. The 24 and 36 deg sweep cases had reference static margins of 15 and 5%, respectively, at the reference sweep angle of 30 deg, giving them absolute static margins of 10.2 and 10.3%. These static margin cases were chosen for comparative purposes with the ASW-19 and SB-13, both of which had a static margin of 10.7%. The 30 deg sweep case had an absolute static margin of 2%. This case was chosen to investigate the gust response at low static margins. The Exulans has a lower design speed than the other aircraft used in the comparative study, making a direct or quantitative comparison difficult. The Exulans models were trimmed at 55.3, 82.4, and 109.4 km/h for the 24, 30, and 36 deg sweep cases, respectively. Both the ASW-19 and the SB-13 were trimmed at 120 km/h for the simulations.

A simulation with a 10 s duration was performed with each of the aircraft models. A gust that produces a nose-down rotation (in other words, a vertically upward gust) was introduced as a disturbance at 1 s into the simulation. The gust has a 1 − cos shape. The gust model is similar to that used in [2]. The gust had a 2 m/s magnitude and a wavelength of 50 m for all cases. The time duration of the gust varied with the true airspeed of the aircraft. In the case of the ASW-19 and SB-13, the gust duration was 1.5 s. The gust durations for the Exulans simulations are different due to the lower trim speeds.

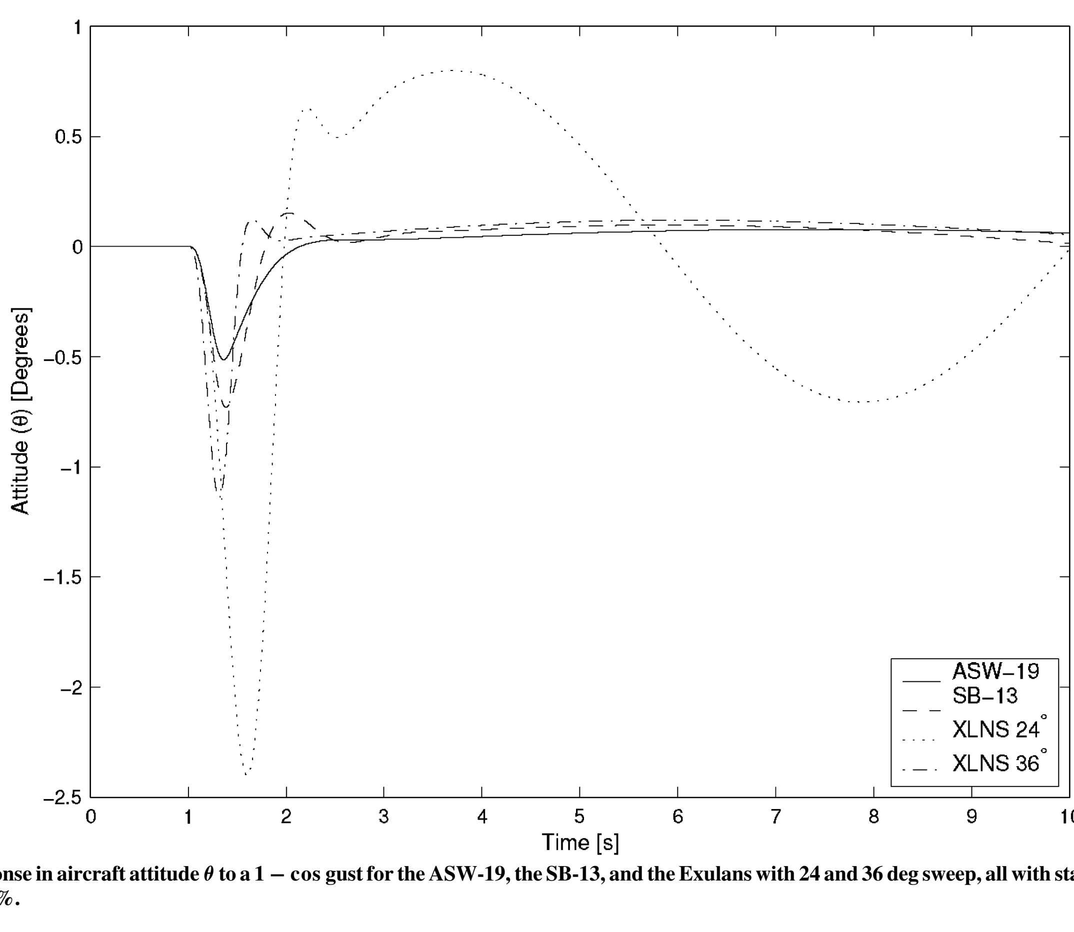

Fig. 5 Response in aircraft attitude θ to a 1 − cos gust for the ASW-19, the SB-13, and the Exulans with 24 and 36 deg sweep, all with static margins just more than 10%.

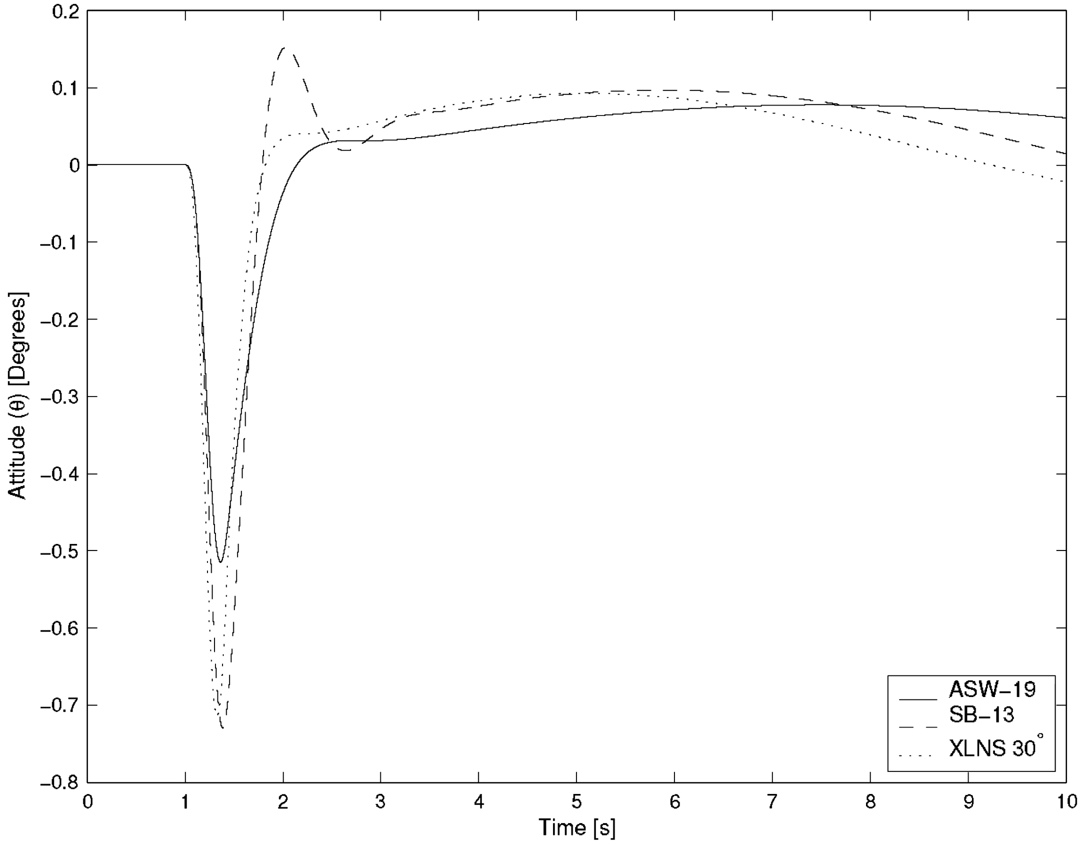

Fig. 6 Response in aircraft attitude θ to a 1 − cos gust for the ASW-19, the SB-13 (both at 10.7% static margin), and the Exulans with 2% static margin and 30 deg sweep.

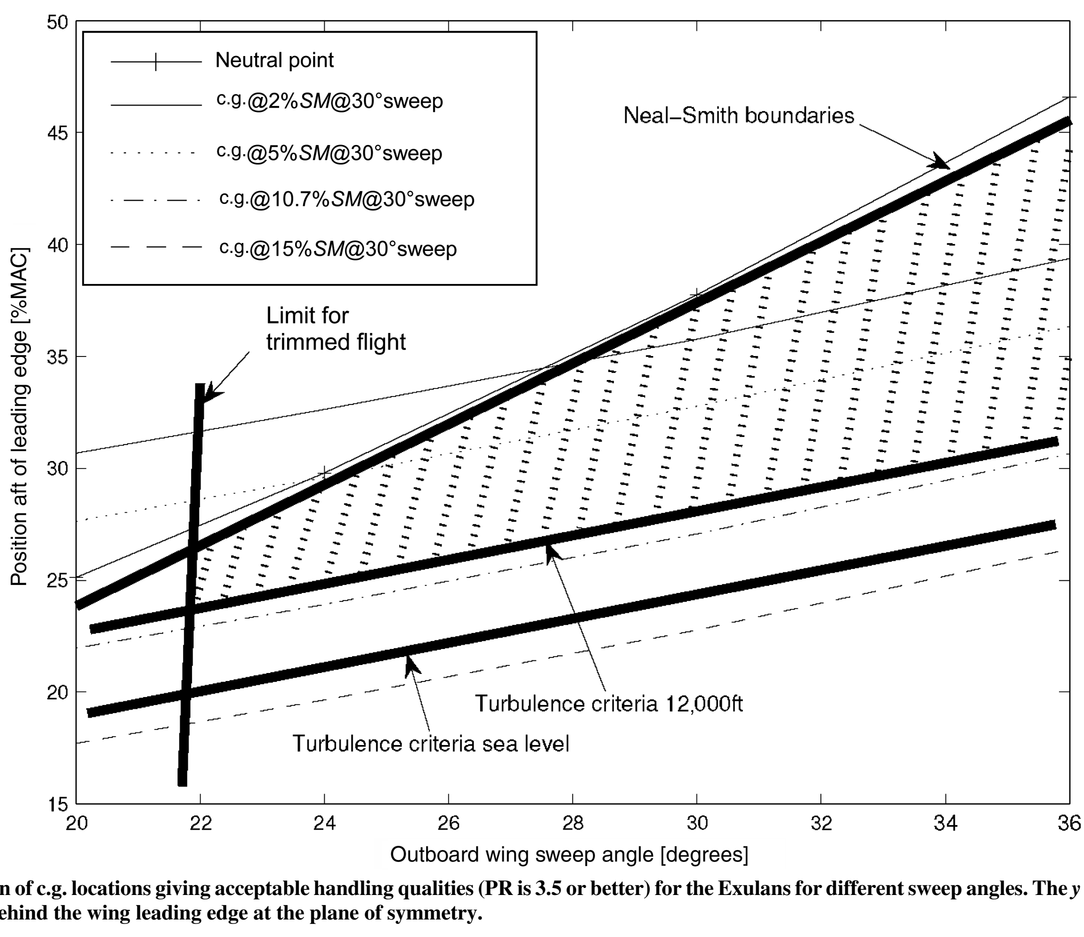

Fig. 7 Region of c.g. locations giving acceptable handling qualities (PR is 3.5 or better) for the Exulans for different sweep angles. The y axis represents the distance behind the wing leading edge at the plane of symmetry.

The results of the simulations are presented in Figs. 5 and 6. The pitch attitudes of the different aircraft are shown as a function of time. Zero degrees is used as an arbitrary reference for the trim attitude for ease of comparison. Short period response is visible for all aircraft while exposed to the gust. The short period mode is rapidly damped out and the phugoid response follows.

The ASW-19 shows a short period mode with high subcritical damping (ζ_{sp} higher than 0.7, but less than 1). In comparison with the ASW-19, the SB-13's short period mode is less damped. The short period motion continues after the gust has been passed. The Exulans also shows a less damped short period in both the 24 and the 36 deg wing sweep case. The short period motions of these simulations are similar to the SB-13. The 24 deg wing sweep case also displays a large phugoid amplitude, but because the phugoid mode has a low frequency, this does not influence the handling qualities negatively. In contrast with the 10% static margin cases, the 2% static margin case with 30 deg sweep of the Exulans shows short period behavior that is comparable with the ASW-19 (see Fig. 6). These simulations show that the low static margin case of the Exulans has a more favorable short period response than its high static margin counterparts, because the short period mode is better damped for this case.

The short period mode is very important with respect to the handling qualities of an aircraft. It stands to reason that, if it is well behaved, the aircraft should have satisfactory handling qualities. The ASW-19 acts predictably as it enters a gust. The SB-13 continues to oscillate after it has been excited by the gust. This makes it difficult for the pilot to anticipate and counter the motion of the aircraft, because gusts are usually random in nature. If the aircraft is still responding to a previous gust while being excited by the next, it is increasingly difficult for the pilot to identify the direction of the disturbance and to apply the appropriate counter for it. If the pilot is unable to do this, he/she may very well be amplifying the motion, rather than damping it.

In summary, a low static margin (2%) yields a more favorable gust response for a gull-wing configuration like the Exulans. This agrees with the work of Mönnich and Dalldorf who found that the SB-13 had improved gust handling qualities at 2% static margin [2].

VII. Aerodynamic Efficiency in the Context of Handling Qualities

In this section, the results of the two handling quality analyses are summarized and superimposed with the efficiency requirements discussed in Sec. III. This provides insight into the compromise between handling and efficiency relating to the gull-wing configuration.

The region of c.g. locations associated with the best Oswald efficiency lies between the E point and the O point of the aircraft, depending on the contribution that the winglets may be making to the effective span. This region is presented in Fig. 2 as the shaded area. The region of longitudinal c.g. locations associated with the most favorable handling qualities is presented as a shaded area in Fig. 7. This region is truncated at the low sweep angles, as these do not provide for trimmed flight. Figure 7 also shows how the c.g. of the aircraft would change with a change in sweep angle given that the outer wings and the winglets are not without mass. Four different c.g. scenarios are plotted.

Figure 8 shows the overlapping region of favorable handling qualities with the region of best Oswald efficiency. The overlapping region represents possible c.g. locations that would result in a c.g. position for an aircraft with both good handling qualities and a high Oswald efficiency.

Figure 9 shows the intersection of the regions of favorable handling qualities and good efficiency plotted again with four different c.g. scenarios.

VIII. Conclusions

A longitudinal handling quality analysis was performed on the gull-wing configuration. The subject of the analysis was the Exulans tailless glider. An analysis was performed using the Neal–Smith

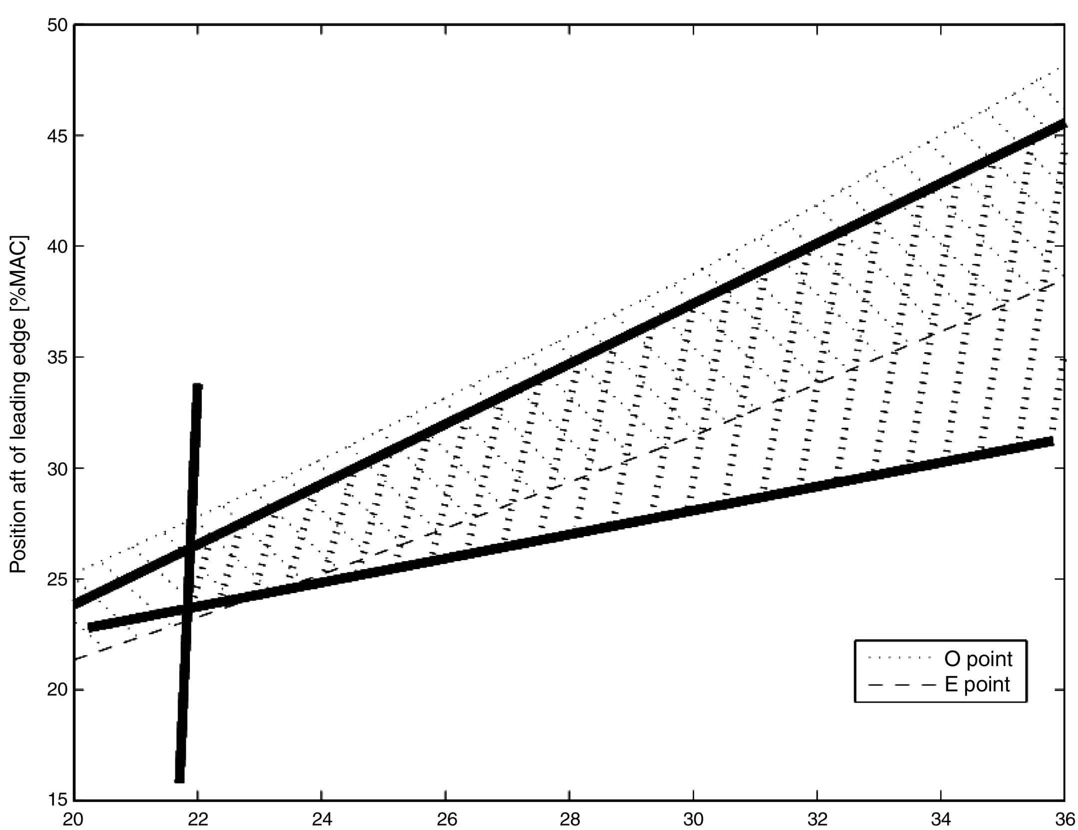

Fig. 8 Superposition of regions of c.g. locations giving acceptable handling qualities and best Oswald efficiency for the Exulans.

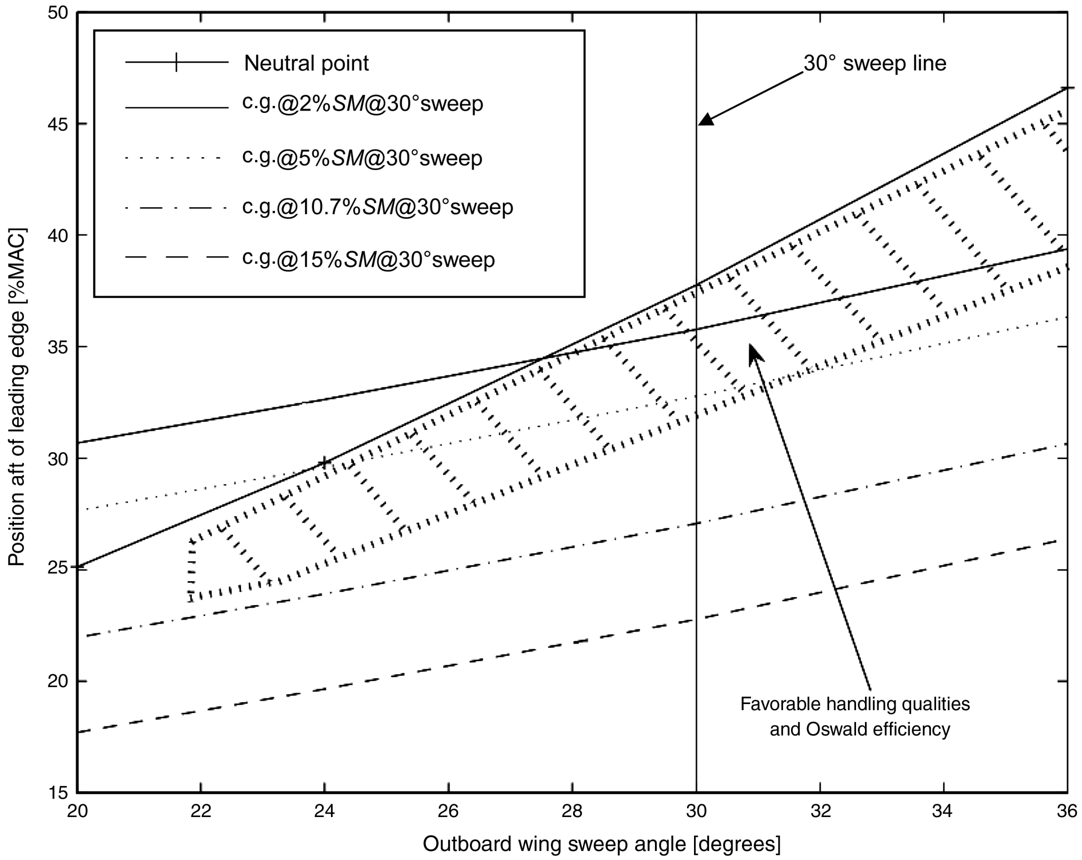

Fig. 9 Region of c.g. locations with both acceptable handling qualities and good Oswald efficiency for the Exulans.

method [3] as well as the Mönnich–Dalldorff flying qualities criteria [2] for tailless aircraft. The following conclusions were drawn from this investigation:

1) A region of c.g. locations exist for the tailless gull-wing configuration where the aircraft will have both favorable pitch handling qualities and high Oswald efficiency.

2) It seems possible to design an aircraft with a gull-wing configuration that has acceptable longitudinal handling characteristics in a gusty as well as a calm atmosphere. The handling qualities of the Exulans during gusty conditions should be good at low altitude but poor at high altitude (12,000 ft) for the case of high static margins.

The following recommendations for further research can be made to better understand the handling qualities of the tailless gull-wing configuration:

1) The handling quality analysis should be extended to lateral dynamics for a range of c.g. locations.

2) The handling quality analysis results presented here cover only angles of attack in the linear lift region of flight. The pitch handling quality study should be extended to extreme angles of attack. Such a study should be used to investigate the handling qualities of the gull-wing configuration during recovery from flight conditions such as stalls and spins for a range of c.g. locations.

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