Improving the Airplane Efficiency by Use of Wing Maneuver Load Alleviation

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It is shown that by deflecting the wing flight controls in response to a change in airplane load factor the maneuvering flight loads may be reduced resulting in a wing weight saving. Five different maneuver load alleviation (MLA) configurations were studied for wing bending load relief on a large 700,000 lb transport airplane. The effect of MLA on an extended wing span design was also investigated. Results show that the airplane studied could have its wing span increased 10% for the same wing weight if MLA were used. The corresponding airplane performance improvement was 13%, resulting in a 10,000 lb payload increase. This design approach also appears attractive for growth versions of the airplane. Design considerations which must be recognized when using MLA are discussed, along with the use of the MLA system for active gust alleviation. Future use of MLA may be expected. The resulting performance benefits may pave the way for the use of flight controls for active gust alleviation and direct lift control.

Introduction

THE laws of aerodynamics clearly establish the aerodynamic performance benefits resulting from increasing the airplane wing span. In most cases the wing span selected for an airplane is the result of a design tradeoff between the wing weight and airplane drag to produce the optimum performance. Numerous attempts to exploit the performance effects of wing span from both the aerodynamic and wing weight standpoint have been made. These include: 1) use of wing tip vertical fins; 2) use of wing mounted engines and fuel pods; 3) coupling of airplane during flight to obtain the performance benefits of their combined wing span, also flying disposable wing tips with fuel pods; 4) use of wing tip mounted engines with exhaust swirl devices to counter tip vortices; 5) use of the variable geometry sweptback wing; and 6) use of flight controls to unload the wing during maneuvering flight. Here the span air loads are changed to move the span-wise center of pressure inboard to reduce the wing bending moment, hence the wing weight.

All of the above systems require extensive analysis to determine if the end produce, the airplane, is really more efficient, or rather just more complicated. The latter being a necessary part of the over-all efficiency evaluation.

The present paper examines the use of deflected wing flight controls to reduce wing loads during maneuvering flight, Item 6. Although the present concept is not new, Ref. 1, it is believed to offer a practical design approach. There are numerous design considerations and those recognized by the author are discussed.

Principle of Operation

The fundamental operation of the maneuver load alleviation systems presented calls for symmetrically deflecting the wing flight controls proportional to the normal incremental acceleration of the airplane.

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For example, if an airplane is designed to develop a load factor of $n = 2.5$, then wing tip controls must be deflected to produce an aerodynamic down-load on the wing proportional to the airplane incremental load factor, resulting in a wing bending load relief at $n = 2.50$. Should inboard wing flaps be used, they would be required to be deflected downward to reduce the airloads on the outer portion of the wing. The airplane drag and wing loads are unchanged at $n = 1.0$ since the controls are deflected proportional to the incremental load factor.

Flight controls are considered to be deflected automatically being directed with proper sensors which may take the form of: a) wing deflection sensors, b) load factor sensors, c) wing angle of attack sensors. While the type of sensors are not defined in this paper, they should be of a fundamental nature, and form a basic part of the airplane.

MLA Systems Studied

A large subsonic swept wing airplane has been studied with five different MLA devices. Figure 1 presents a planview of the airplane studied. All outboard controls are located outboard of the 70% semispan position, while the inboard flap affects the wing inboard of the 40% semispan station.

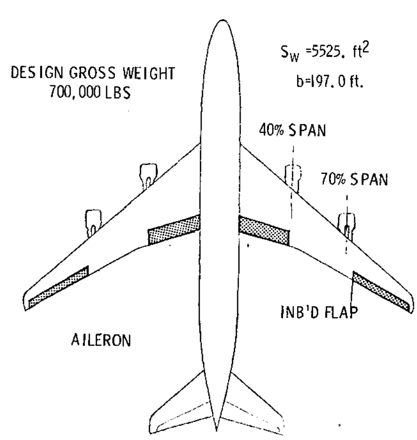

Fig. 1 Plan view of airplane.

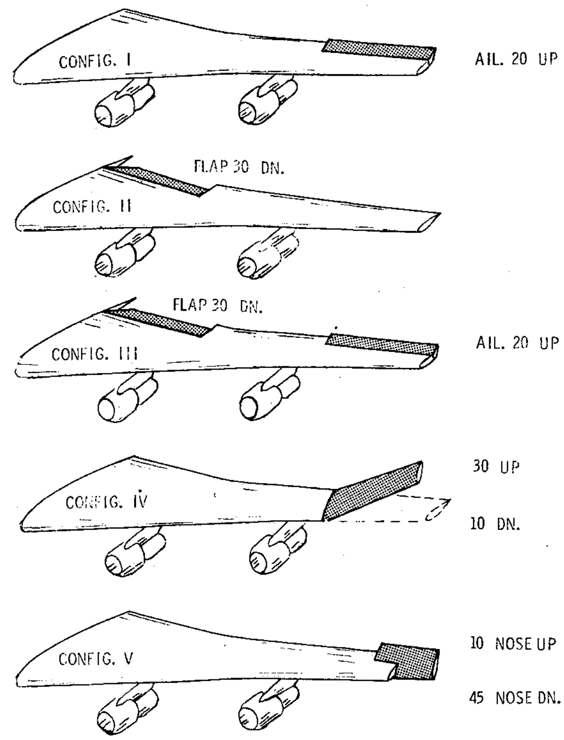

Fig. 2 MLA configurations studied.

Flight controls studied consisted of the following arrangements:

1) Outboard ailerons. These are deflected symmetrically upward a maximum of 20°. 2) Inboard wing flaps. These are deflected downward a maximum of 30°. 3) Use of both 1 and 2 together. 4) Hinged wing tip. In this arrangement the wing is hinged at the 75% span position on an axis normal to the wing elastic axis. A constant spring load force is assumed to hold the wing in the 1.0g position. Deflection limits are set up for 10° tip down and 30° tip up. 5) Tip aileron. A large horn balanced aileron over the outer 10% of the wing span is freely pivoted. Hydraulic dampers and a control tab are used to regulate its motion. Deflection limits are 45° nose down and 10° nose up. Figure 2 shows a sketch of each of the above control configurations.

Method of Analysis

The analysis consisted of statically evaluating the design maneuvering loads and calculating the wing weight change resulting for the various control configurations. This was first done for the basic airplane, and then for the same airplane having a 10% and a 20% wing span extension. Span extensions were made by extending the wing leading and trailing edges changing the wing dead weights only outboard of the outboard engine nacelle.

This was accomplished by using a digital aeroelastic wing loads and weight program developed by the Boeing Structure Loads Group. The program has been in use for some time and calculates the design static wing loads and the wing weight in detail. Aerodynamic wing data were well represented throughout the airplane Mach number speed range. The program was first calibrated with proper factors to represent realistic wing weights and geometry.

First the program uses a wing stiffness distribution and calculates the airloads for the deflected wing. This includes the evaluation of the span loading with wing deflection. Here the complete airplane is balanced with the necessary tail load at the desired load factor.

The next operation is to repeat the first operation using different wing stiffness distributions until the wing stiffness matches the allowable skin loads which is represented in the program. The third and last operation is to repeat this process for each flight condition and then selecting the critical wing section properties for each spanwise station. At this point the wing weight is calculated. Each wing was analyzed for a total of 17 different airplane weight, c.g., and speed conditions.

The critical flight conditions for the airplane investigated were in most part for the flaps up low-speed, high angle-of-attack flight conditions. High-speed flight conditions can affect parts of the outboard wing especially when the aileron is used. In this case a regulation of the load alleviation with airspeed may be necessary. High and low-speed flight conditions critical for the present airplane were included in the present analysis. Local flap and aileron loads may increase at high speed. This weight increase will depend upon the MLA system used. Although this evaluation is certainly not a complete wing load analysis it is believed to represent all of the flight conditions critical for maneuvering flight.

Results

The basic wing had a wing structural box weight of 43,100 lb. The structural weight saving due to MLA is presented in Table 1 for the different configurations and span extensions. From this weight must be subtracted that due to material put back into the wing in order to maintain the same 1g stresses as will be discussed. In addition, weight must be added for the nonstructural material used to extend the wing span. No weight allowance has been made for controls necessary to operate the sensors as these weights may be expected to be small.

Final weights are plotted against wing span in Fig. 3. For comparison purposes the weight of extending the wing

Table 1 Airplane weight change due to MLA[a]

Span ratio		1.0	1.10	1.20
Base airplane	Structure	0.	9,972.	20,970.
	Non str.	0.	680.	1,290.
	Fatigue*	0.	0.	0.
	Wt. change	0.	10,652.	22,260.
Aileron	Structure	−4,066.	1,470.	7,256.
	Non str.	0.	680.	1,290.
	Fatigue	539.	1,457.	2,083.
	Wt. change	−3,527.	3,607.	10,629.
Aileron 5% c.g. shift	Structure	−3,318.	2,476.	8,456.
	Non str.	0.	680.	1,290.
	Fatigue	485.	1,310.	1,870.
	Wt. change	−2,833.	4,466.	11,616.
Inb'd flap	Structure	−2,454.	5,574.	14,850.
	Non str.	0.	680.	1,290.
	Fatigue	572.	818.	677.
	Wt. change	−1,882.	7,072.	16,817.
Inb'd flap and aileron	Structure	−6,340.	−1,786.	2,414.
	Non str.	0.	680.	1,290.
	Fatigue	1,100.	2,294.	3,076.
	Wt. change	−5,240.	1,188.	6,780.
Bending wing tip	Structure	−7,034.	−2,954.	874.
	Non str.	0.	680.	1,290.
	Fatigue	660.	1,420.	1,810.
	Wt. change	−6,374.	−854.	3,974.
Tip aileron	Structure	−8,198.	−4,334.	580.
	Non str.	0.	680.	1,290.
	Fatigue	967.	1,480.	1,977.
	Wt. change	−7,231.	−2,174.	3,849.

[a] Fatigue material required to maintain basic airplane 1.0g tension stress level.

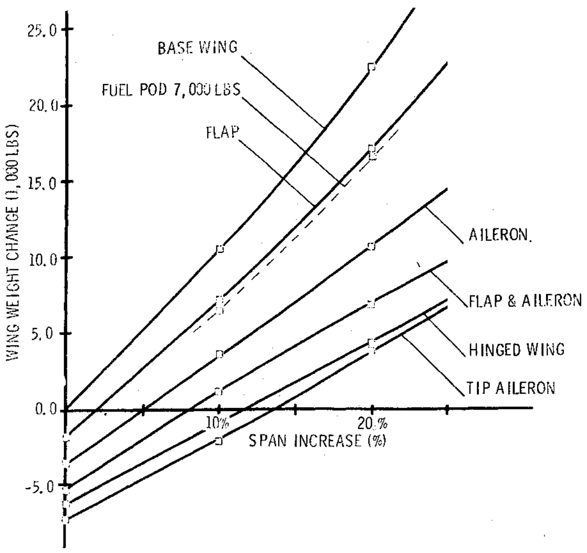

Fig. 3 Change in wing weight due to use of MLA.

span without MLA is shown along with the effect of providing a 1000 gal fuel pod at the 85% wing semispan location. From Fig. 3 it appears that a 10% airplane span extension is possible for the same wing weight.

The airplane performance improvement for a 10% span extensions shows a 10,000 lb airplane payload increase. An estimated payload range curve for this airplane is shown in Fig. 4. It should be noted from Fig. 3 that had the wing been extended without using MLA the wing weight would have increased by nearly 10,000 lb. This indicates that the span selected for the base airplane is near optimum since an even wing weight payload tradeoff exists.

In addition to the payload improvement, other performance benefits occur. Two of these improvements are: a) 1500 ft increase in initial cruise altitude, b) 1.0 PNdB improvement in community and landing noise. It should be noted that these performance gains are not in conflict with any other normal type of airplane growth improvement, hence, truly represent an airplane efficiency improvement.

Figure 5 shows the spanwise lift distribution of the basic airplane compared with that for a wing having a 10% span increase and using the aileron MLA configuration. One typical flight condition is shown. By dividing the root bending moment by the wing shear a spanwise center of lift is obtained. This is shown to be practically the same for both wings.

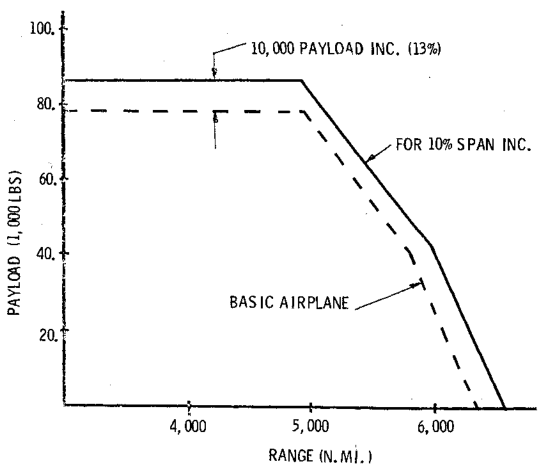

Fig. 4 Airplane payload range increase.

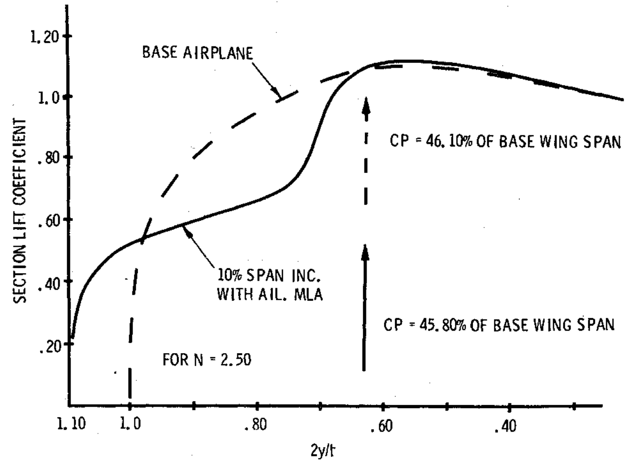

Fig. 5 Span lift coefficient distribution using aileron MLA.

The resulting change in the wing panel weights is shown in Fig. 6, plotted in terms of percent span. The 10% increased span wing has no geometry change inboard of the 70% span position. Weight changes requiring the wing material to be added to maintain the same 1.0g stress level are distinguished from the weight changes due to MLA. It should be noted that all large MLA weight changes occur near or outboard of the outboard engine nacelle which may require a wing redesign. On the inboard wing stations weight changes are smaller and may be taken care of by changing skin gages. This is one reason MLA is attractive for providing performance growth to existing airplanes.

Design Considerations

The design of a MLA system involves other considerations which must be recognized and analyzed. Those problems recognized by the author will be discussed in the following sections.

1 Wing Stall Characteristics

In order to relieve the high angle-of-attack wing loads the system must guarantee load relief well into the airplane stall. An examination of wing section wind-tunnel pressure data showed that wing spoilers lost effectiveness as the stall was entered. For this reason wing spoilers were not considered satisfactory. Figure 7 shows how the tip wing section lift coefficient changes as the airplane enters the stall. The outboard aileron and horn tip aileron behaved in a satisfactory manner as they maintain the lift relief well into the stall.

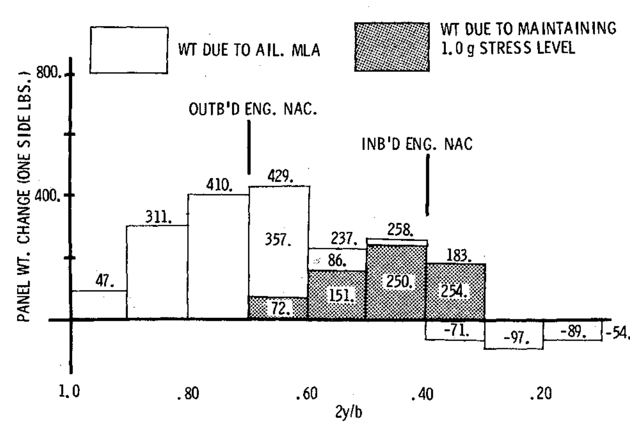

Fig. 6 Wing panel weight change.

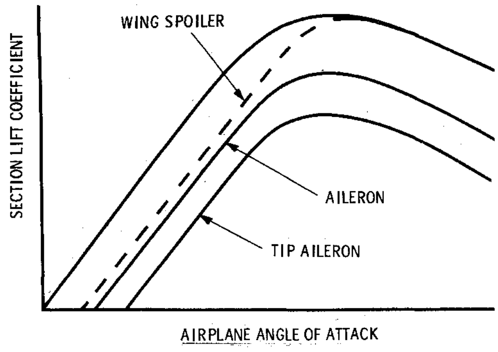

Fig. 7 Wing tip section lift coefficients.

2 Wing Fatigue Life

The wing bending material is reduced because of MLA reducing the design airloads. The 1.0g airloads, however, are not effected. This will result in an increase of the wing 1.0g stress level. The base wing studied was known to have a satisfactory 1.0g stress level. For this reason bending material is added back into the load alleviated wings whenever the 1.0g tension stresses exceeded the maximum stress indicated for the base wing. This weight allowance can only be an approximation. The reason being that a fatigue analysis is a complex problem which involves different flight conditions including the ground to air cycle of the wing.

In order to approximate this weight increase the 1.0g combined stress, due to wing torsion and bending, was calculated for the maximum wing depth at each station along the wing span as shown in Fig. 8. Similar stresses were evaluated for the maneuver load alleviated wings. When wing section stresses were greater than the maximum value indicated for the base wing the section tension material weight was increased proportional to the stress increase as indicated in Fig. 8. It is noted that the maximum stress level occurs over the mid-forty percent of the wing span.

Ways of avoiding the adverse effects of the 1.0g stresses should form a part of future research. This can take the form of wing preload, or of gluing plastic tapes of Boron or Carbon fibers to the wing stringers on the under side of the wing.

3 Change in Airplane Stability

Unloading the wing tip of a swept wing airplane with increasing airplane load factor has a destabilizing effect on the airplane. This causes a forward movement of the airplane's dynamic neutral point, leaving the airplane static neutral point unchanged. In some airplanes a small forward movement of the dynamic neutral point may be welcomed as the stability margin at low airspeed may be higher than desired. The use of an inboard flap for MLA may be quite destabilizing depending upon its interaction with the horizontal tail. Figure 9 shows the change in the dynamic neutral point for the configurations studied. Here the tip controls show about an 8% forward movement of the dynamic neutral point with increasing wing span. One reason this neutral point shift is nearly constant with span increase is that the aileron and hinged wing tip both start near 70% of the basic wing span, hence more load alleviation is used as the wing span increases.

All of the MLA devices were evaluated for the established c.g. positions of the basic airplane. As the airplane is balanced for each flight condition lower maneuvering tail loads occur when MLA is used. If the same c.g. range were to be maintained a more forward airplane c.g. would be required and the wing weight would be increased. In order to show the effect of c.g. on the weight saving expected for MLA the aileron configuration has been analyzed for a 5% forward shift of the entire airplane c.g. range. Each flight condition has a 5% c.g. shift forward. These results are shown in Fig. 10 and are compared with the basic airplane showing that about 15% of the basic weight saving with MLA may be attributed to the reduction of the balancing horizontal tail load.

The regulation of both the dynamic and static stability may be controlled artificially. On the other hand, airplane

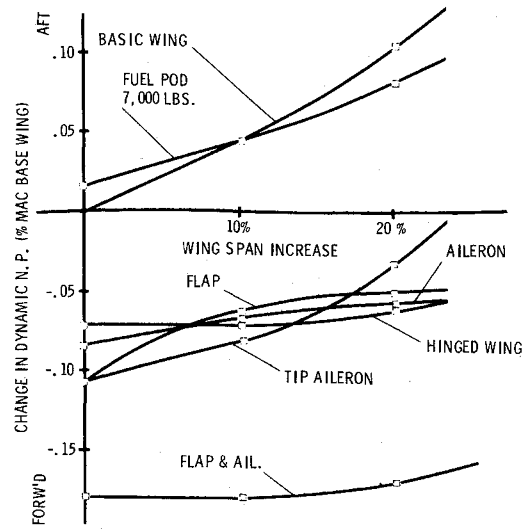

Fig. 9 Change in airplane dynamic neutral point.

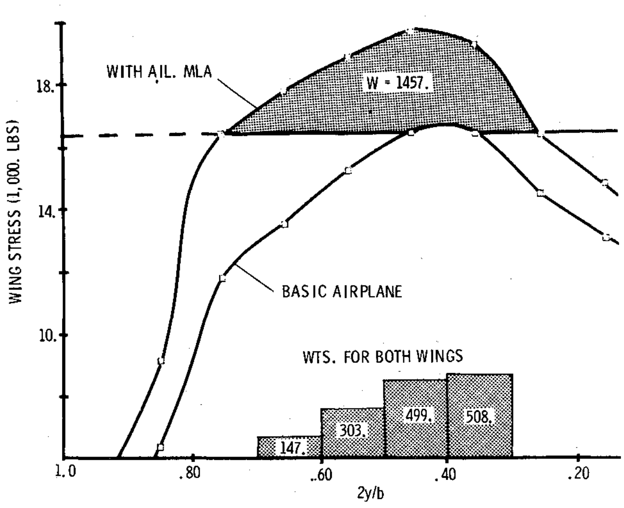

Fig. 8 Max. 1.0g combined wing stress.

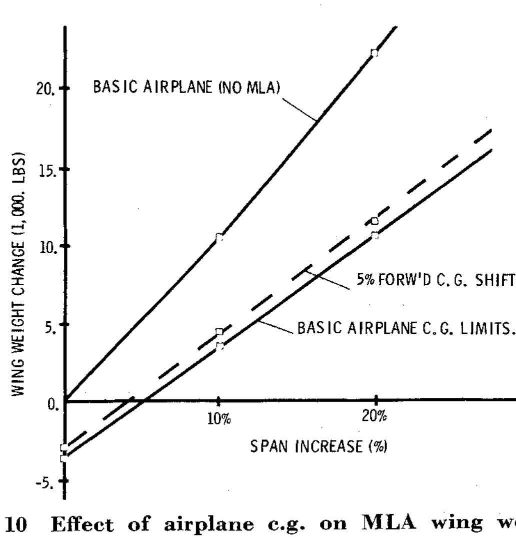

Fig. 10 Effect of airplane c.g. on MLA wing weights.

c.g. limit changes may involve major airplane configuration changes such as relocating the landing gear and changing the body length. This is another reason MLA offers an attractive means of providing span growth to an existing airplane.

4 Control Reversal

Outboard ailerons on swept back wing airplanes generally have a low-control reversal speed. For this reason, these controls are generally locked out at high speed. Operating the ailerons symmetrically will not effect the control reversal speed, but will reduce and even reverse the MLA load relief at high speed. The airplane studied had positive airfoil camber and wing twist in the outer portion of the wing, which causes the spanwise wing center of pressure to move inboard with an increase in airspeed during level flight. Because of this a smaller amount of MLA action can be satisfactory at the higher speeds. Should the reduced MLA action at the higher airspeeds reverse causing undesirable loads the system may be regulated with airspeed or cutoff completely.

5 Wing Flutter

Wing flutter is an important factor to consider when using MLA to extend the airplane wing span. A wing flutter analysis has not been made for the MLA systems studied, but it may be expected that the wing flutter speed margins will be reduced for the airplane configurations having the extended wing span.

Moving the outboard engine nacelle further outboard as the wing span is increased may be used to maintain the wing flutter speed margins. This design approach is desirable as it also provides wing bending load relief. The net performance gains may, however, be limited as moving the engine will cycle other airplane changes, such as an increase in the vertical and horizontal tail size, possible relocation of the main landing gear, and increasing the wing fatigue stresses because of the increased ground to air cycle wing stresses.

Future airplanes may need a different design approach for the prevention of wing flutter. The author believes that it is not unreasonable to use a MLA tip control also as a wing flutter damper. In order to accomplish this a high-degree of reliability must be assured. It would be necessary to show that any possible failure would not produce a control motion phase shift which would induce wing flutter.

Future flutter research should study the active use of wing controls for wing flutter prevention. This work should first determine the desired control motions to suppress wing flutter. After this is done the necessary electrical, hydraulic or mechanical systems may properly be designed.

6 Gust Load Alleviation

Although the airplane studied was not gust critical wing tip MLA may be expected to relieve the wing gust loads. Once wing tip controls are used for MLA their use for gust alleviation may become a necessity. If the airplane studied had less wing sweep gust loads would be expected to be critical. In this case the use of the wing tip controls for active gust alleviation would become a necessity.

Applications of Gust Alleviation to a Transport Airplane

If gust alleviation can be used to extend the airplane fatigue life, or to provide an improved passenger ride quality, its use on transport aircraft would be desirable. A limited analysis of this problem has been made to show the nature of the airplane response when subject to a discrete gust. Here a wing tip aileron was used to obtain gust relief.

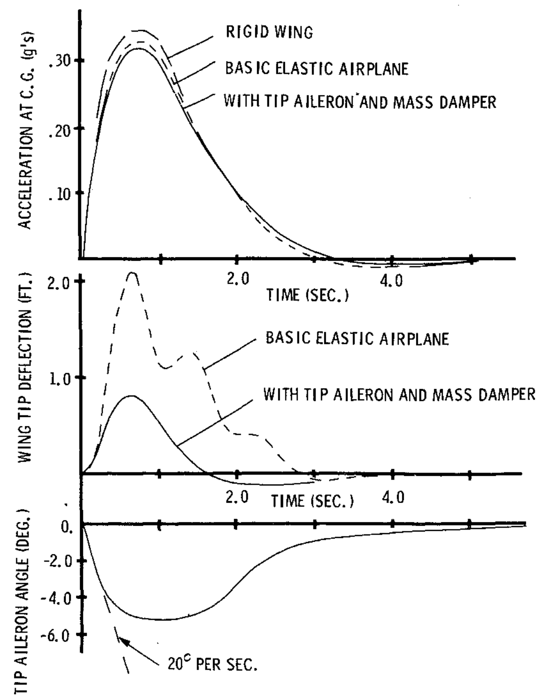

Fig. 11 Airplane gust response.

The gust level was determined from gust measurements made during severe thunderstorm conditions, Ref. 2. An analysis of these data is presented in Appendix A. It is shown that a 50 ft per sec gust velocity developing its maximum value over a 400 ft gust rise distance is a reasonable value to use for the present analysis.

The response of the present airplane using a ramp gust as specified above has been made for a cruising flight condition. Here the airplane was considered rigid except for the wing which was represented by a single wing bending mode. These results are shown in Fig. 11.

The response for the rigid airplane is also presented indicating that only about 8% gust relief at the airplane c.g. results from wing bending relief. Next the tip aileron having proper mass balancing and damping was subjected to the same gust response. This resulted in damping of the wing motion with only a small change in acceleration at the airplane c.g. This damping is beneficial from the gust fatigue standpoint.

This is only a limited analysis of the airplane response characteristics but indicates that a tip MLA control used for gust alleviation may be used for wing gust stress relief, and may improve the wing fatigue life. It can not be expected to improve the airplane ride comfort to any appreciable extent. It should be noted that if a device is used to improve the wing fatigue life its operation at small amplitudes is important, as well as, the avoidance of any small hunting cycle that may be developed due to the gust sensors.

An inspection of the tip control movement in Fig. 11 shows that if power operated controls were to be used a maximum control rate of 20° per sec would be sufficient. Present hydraulic controls for large airplanes have maximum movement rates of 30 or 40° per sec. This means that present hydraulic systems may be expected to handle the operation of an active gust alleviation system. Should gust relief for passenger comfort be desired, operation of the inboard flap will be necessary.

Discussion of Results

The most simple use of MLA would employ rigging the outboard ailerons up during flight at the high-airplane gross weights during the early part of the flight. The pilot could

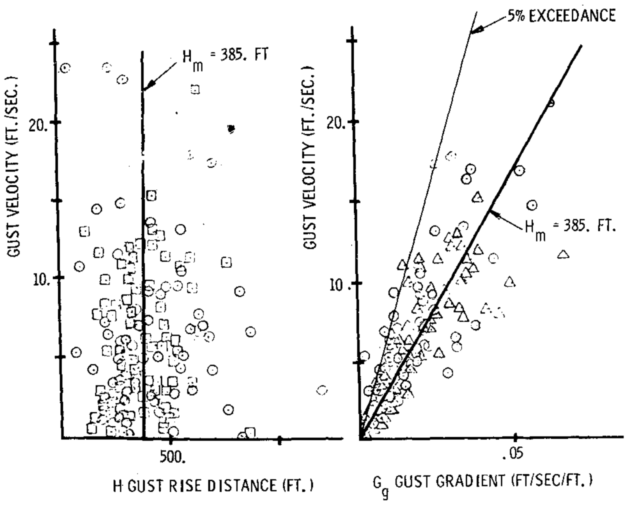

Fig. 12 Gust velocity and gradients.

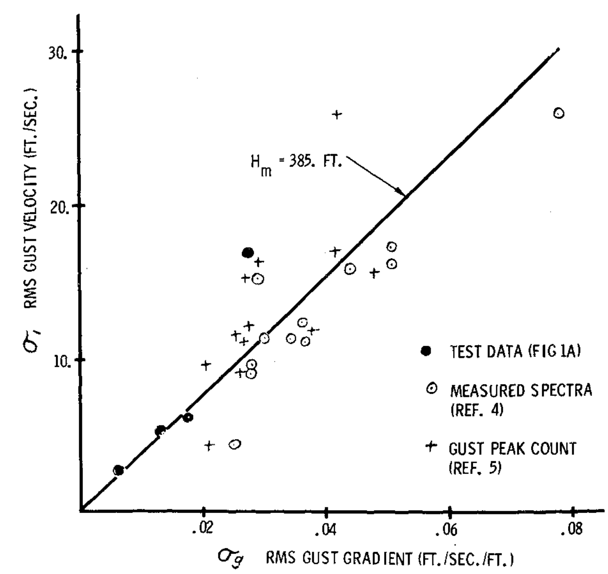

Fig. 14 Relation between the rms gust velocity and gradient.

then reduce this deflection as the flight progressed and a net performance gain achieved. The next more complicated arrangement and proposed in this paper is to deflect the ailerons symmetrically with incremental load factor. This must be done automatically separate from the pilot control operation in order to prevent the pilot from removing the load alleviation at the wrong time. As the airplane dynamic stability is affected a linear response of the aileron with load factor is desired in order to maintain reasonable pilot control forces. An airplane accelerometer or other sensor may be located at the airplane c.g. unless gust alleviation is desired. In this case the sensor should be located on the wing to insure proper results. This location in itself must be studied to insure that the structural wing deflection modes are not excited.

The hinged wing tip has many desirable features and should not be overlooked as a practical solution. For the airplane analyzed a 400,000 lb spring load on a 12 in. arm is required to hold the wing tip in the 1.0g flight position. This load should remain essentially constant with wing tip deflection. Use of high-pressure liquid springs may provide a practical system. Here a small amount of hydraulic power could be used to maintain the proper fluid pressure. For such a system a small control tab used on the tip could be used to supply trim for the hinged wing and also be used for flying the wing tips for airplane roll control. This type of control resembles that studied in the 1950's when flying wing tips with fuel pods were studied. Perhaps using springs to hold the wing tips in position instead of the fuel mass may relieve the adverse wing flutter characteristics experienced with some flying wing tips. This type of control automatically provides MLA without requiring additional control sensors.

In Fig. 3 it was shown that an inboard wing flap provided a wing weight saving when used for MLA. This load alleviation was obtained statically by allowing the airplane to be at a smaller angle of attack when the design load factor is reached. Whether any appreciable load relief is possible when the dynamic airplane response is considered would require a dynamic analysis.

It should be noted that the MLA action of the inboard wing flap is also applying Direct Lift Control which may be beneficial. The gust relief using this system may become critical and may require using the wing tip MLA system along with the inboard flap.

The use of a large horn type tip control may also be attractive. For this type of control a small vertical fin may be required to properly seal the leading edge wing slot. During the analysis it was found that in order to unload the wing tip a large wing tip nose down deflection was required. The reason for this is that as the wing tip is unloaded the wing span loading is changed causing a upwash at the tip due to the wing induced angle-of-attack change. This makes the wing tip control more effective as a MLA control but also requires a large deflection. The wing torsion loads are lower which reduces the wing combined stress resulting in a smaller wing weight. Like the hinged wing no special MLA sensors are required. A control tab used with the tip control may be used for trim and to provide lateral airplane control. Proper mass balancing of this control may also provide an active type wing flutter damper.

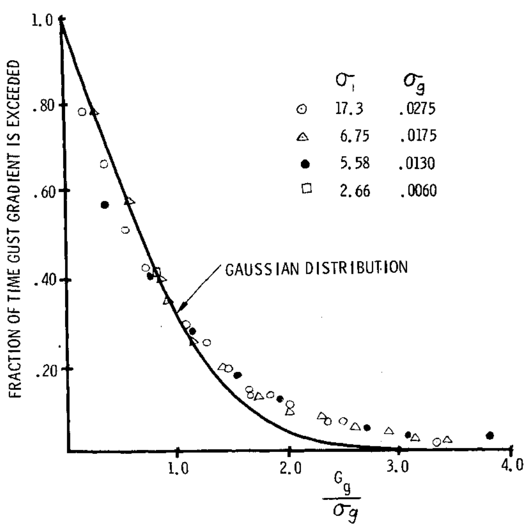

Fig. 13 Distribution of gust gradients.

Conclusion

Performance benefits using MLA have been examined and found to give a reasonable improvement in the airplane efficiency. Problems related to the design of a MLA system are recognized and some need more study before a design application is possible. Future use of MLA may be expected, and the performance benefits may pave the way for other uses of flight controls to improve both the airplane efficiency and flying qualities. All types of systems should be studied from the standpoint of obtaining a simple design.

Appendix A: Analysis of the Atmospheric Gust Velocity Data

The distance the airplane must penetrate a gust before the maximum gust velocity is developed is very important as it is a factor determining how fast the active gust alleviation controls must act in order to accommodate the gust. A knowledge of this before an involved spectrum analysis is made may not only save time, but will provide the preliminary design engineer with useful information. For this reason, a detailed analysis of the gust data is presented in this appendix.

Four gust velocity time history records from Ref. 2 were analyzed on a digital computer. This was accomplished by using a broken line to represent the record. The line was broken at every point in which a velocity slope change could be detected. This amounted to a finite differentiation of the gust time history. Sample data are shown in Fig. 12. The mean gust rise distance H_m as defined below and evaluated from Fig. 14 is indicated on this figure.

An exceedance count was then made of the calculated values of the gust gradients σ_g. By properly plotting these values an rms gust gradient σ_g was found. This is defined as a truncated rms gust gradient as it does not include many of the smaller velocity fluctuations. A summary plot of these results is presented in Fig. 13 along with the truncated rms gust velocities taken from Ref. 2. These values are compared with the Gaussian distribution curve and found to be in a reasonable agreement for the smaller gust gradients.

From Rice's equation a relationship exists between the ratio of the integral of the zero and second moment of the spectra equation. The integral of the zero moment defines the rms gust velocity, while the integral of the second moment defines the rms gust gradient. By limiting the upper limit of Rice's equation to σ_2

$$N_0 = (1.0/2\pi)\left(\int_0^{\Omega_2} \Omega^2\phi(\Omega)d\Omega \Big/ \int_0^{\Omega_2} \phi(\Omega)d\Omega\right)^{1/2} = \sigma_g/\sigma_w$$

giving the following equation for the truncated rms gust gradient.

$$\sigma_g = N_0(\sigma_w/\sigma_1)\sigma_1 = \sigma_1/H_m$$

hence

$$H_m(\sigma_w/\sigma_1) = 1.0/N_0$$

Here H_m is defined for the truncated rms gust velocity σ_1. For use with the spectra equation, H_m should be increased by the ratio (σ_w/σ_1) as N_0 is independent of the gust velocity. For the above equations: Ω = spacial frequency (rad/ft); $\phi(\Omega)$ = spectra equation; σ_g = truncated rms gust gradient defined for Ω_2 ft/sec/ft; σ_1 = truncated rms gust velocity defined for a lower frequency limit Ω_1, and the upper limit Ω_2 fps; σ_w = true rms gust velocity fps; N_0 = number of positive gust velocity crossings per foot at zero gust velocity; H_m = mean gust rise distance based upon σ_1.

The value of H_m defined here is identical to the λ_0 value defined in Ref. 3 where it is referred to as a characteristic wavelength. In the preceding reference the author discusses the futility of calculating a rms gust gradient because of the infinite value of the integral of the second moment. For the present study gust frequencies within the measured spectra range are only of interest, hence, the gust gradients will be recognized to be limited to these frequencies. Whether the gust gradient defined here can be shown to meet the probability of occurence laws is not thoroughly investigated. This will require further work by engineers qualified in this field.

Values of σ_1 and σ_g noted in Fig. 13, as well as, data from Refs. 4 and 5 are shown in Fig. 14. Values of σ_g from the latter data were evaluated from N_0 values. The radial line drawn in Fig. 14 represents an average value of H_m = 385 ft.

The present analysis suggests that if the probability of occurence of gust gradients can be established and properly related to the gust velocity a logical base for forming a discrete type of gust may be established. This would be very useful for the analysis of many types of engineering problems prior to subjecting them to a complete spectrum analysis.

References

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