PREDICTING THE EFFECTS OF NEW TECHNOLOGIES ON AIRCRAFT STRUCTURAL MASS : UCAV CASE STUDY

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Abstract

This paper presents the results of a case study of an unmanned combat air vehicle (UCAV) concept incorporating new technologies associated with advanced materials, enhanced agility, low observability and high structural manoeuvre limit, the latter made possible by the absence of a crew.

A newly developed mass prediction model (AMBER) was used in the study to estimate loads, structural masses, centre of gravity position and pitch inertia. The method employs idealised structural analysis to size the aircraft framework. This allows more accurate predictions in the aircraft conceptual design phase than existing statistically based methods and provides design insights into the aircraft configuration and feasibility.

The AMBER results quantify the effect of the UCAV technologies on the aircraft structural design and mass properties and show that the concept is feasible. Contrast with a manned fighter shows the UCAV to be more capable, but heavier due to the increase in structure mass being greater than the saving in equipment mass. The detail of the results and the insights provided by AMBER lead to the conclusion that the method is a valuable technique in the design of future innovative aircraft concepts.

1 Introduction

The prediction of mass for aircraft of innovative design and employing new technologies when the aircraft is in the conceptual design phase is an important part of the analysis of future designs. In the early design stages current methods of mass prediction are frequently based on parametric algorithms derived from statistical analysis of previous aircraft. Extensive data on aircraft geometry and performance for such aircraft are available and there are many aircraft examples to use in the analysis. However due to reliance on historic data, such methods prove to be inadequate in predicting mass for aircraft using new technologies and configurations.

To model the effects of innovative concepts using statistical methods requires the application of ‘technology factors’. Even with such devices, statistically based methods do not provide the required level of sensitivity to detailed changes in aircraft geometry and materials. These difficulties present a fundamental weakness in the development of new aircraft designs.

In predicting aircraft structural mass, research has shown that analytical design based methods offer the prospect of improved accuracy. Developing such methods could provide an alternative to existing statistical techniques. A research programme was instigated to investigate the potential of design based methods in the early design stages. The objective of this work has been the generation and development of a method of structural mass prediction capable of estimating the effects of emerging technologies on aircraft configurations. The research has developed an analytical design based method called AMBER (Aircraft Mass and Balance Routines).

The background to the development of the new method, together with details of the theory and illustrative applications to specific design problems were presented in [1][2]. Four case studies have been described [3] that predict the effects on aircraft structural design and mass of introducing new technologies to a lightweight combat aircraft. The first three studies were separately concerned with (a) adopting new lightweight materials and structural layouts, (b) enhancing aircraft agility, and (c) designing for lower observability. The final study combined all of these technologies into a single design concept (called a ‘new generation fighter’ or NGF). The results from each of the studies were compared to show the implications of introducing these technologies.

This paper continues the evolution of the NGF by incorporating UCAV features. These include removal of crew-related equipment, addition of datalink avionics and provision of a much higher structural manoeuvre limit.

The paper begins by selecting the design features to be incorporated into the UCAV concept and discussing the implications on combat manoeuvring and structural limit. This is followed by the structural analysis and development of the previously designed NGF required to incorporate the UCAV features. The effects on mass and planform are then described. Finally conclusions are drawn relating to the feasibility of the concept and the value of the insights provided by the AMBER method.

2 UCAV Design Characteristics

2.1 Selection of UCAV Features

The principal advantage of the UCAV is the removal of the threat to the crew. Without crew on-board, the design constraints imposed by physiological aspects, together with associated equipment, can also be removed. The aircraft also becomes more appropriate to missile design philosophy, permitting an increased manoeuvre limit and reduced ultimate factor.

For the UCAV concept of this study, the crew and their associated equipment are removed, datalink avionics added and the structure strengthened to be able to withstand 22g ultimate load capability (ie a 20g limit with an ultimate factor of 1.1). The ultimate factor was reduced to 1.1 from the manned aircraft value of 1.5 in line with missile design practice. It is also consistent with the reduced operational exposure required of a UCAV.

2.1 Combat Manoeuvring

The ability to turn aggressively is an essential attribute for an aircraft designed for close combat. The advent of sophisticated weapons systems has not removed the significant advantage possessed by an aircraft that can achieve a higher turn rate than an opponent. The ability to maintain speed is also a desirable characteristic such that on completion of one manoeuvre the aircraft retains sufficient energy to commence a second without requiring an extensive acceleration period. Such attributes are provided by typically high maximum lift (through high incidence and low wing loading), high structural manoeuvre limit and high thrust to weight ratio.

For example, an aircraft able to complete a 180° heading change in just one second less than an opponent would possess a significant advantage in gaining the opportunity for the first shot. However, if the higher turn rate results in the aircraft emerging from the manoeuvre at a lower speed than the opponent, then the latter may gain the advantage.

The combat manoeuvrability of competing aircraft may therefore be analytically compared using two parameters :

- the time to complete a given heading change,
- the change in speed during the heading change.

With a 20g limit, the UCAV will possess a combat manoeuvre advantage. This advantage will be briefly considered before presenting the structural analysis.

2.2 Structural Limit

Manned combat aircraft are designed with maximum normal accelerations of typically between 7 and 9g. Without the physiological requirements of the crew, unmanned combat aircraft are being postulated with a limit of 20g. Figure 1 shows the classical analysis of turn rate at constant height versus speed for a representative UCAV. It can be used to outline the advantages that a 20g limit bestows on an aircraft.

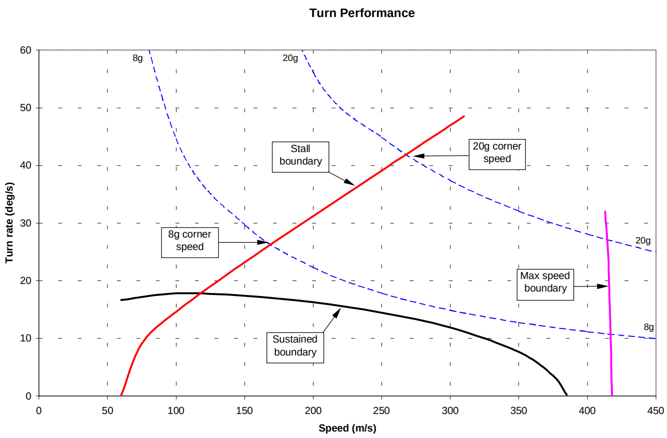

Figure 1 Turn performance plot

The diagram shows lines of constant g, together with the stall boundary (maximum lift), sustained boundary (maximum thrust) and maximum speed boundary for one altitude, in this case sea level.

The sustained turn boundary is marked by the condition where thrust equals drag and so the speed and the turn rate can be sustained. At speeds and turn rates below the boundary there is excess thrust available and so the aircraft could accelerate or climb. However at speeds and turn rates above the sustained boundary, drag exceeds thrust and so the aircraft must either decelerate or lose height. In this condition turn rates are termed instantaneous, since for a constant height turn, the aircraft must slow down thereby changing the turn rate.

The stall boundary marks the limit imposed by maximum lift. Should the aircraft attempt to fly to the left of this boundary it will stall. Some aircraft deploy high lift devices during manoeuvres to effectively move the stall boundary to the left.

The maximum speed boundary marks the limit imposed by structural or equipment characteristics such as aeroelastic stiffness, canopy strength and ejector seat envelope.

The maximum turn rate is achieved where the stall boundary intersects the maximum structural limit. The speed corresponding to this condition is termed the corner speed and is marked on the Figure for aircraft having an 8g and a 20g limit.

For an aircraft with the boundaries presented in Figure 1 and a structural limit of 8g, a manoeuvre beginning at say 300m/s commences with a turn rate of 15°/s. Being above the sustained (maximum thrust) boundary and maintaining a constant height, the aircraft decelerates, moving up the 8g line, until at the corner speed of 170m/s a turn rate of 26°/s is achieved. From this point the aircraft moves down the stall boundary, continuing to decelerate with turn rate decreasing, until the aircraft drag balances the available thrust (ie the sustained boundary is met). At this point the speed of 120m/s and turn rate of 18°/s are maintained.

For an aircraft of the same mass, aerodynamic and propulsion characteristics but with a structural limit of 20g, a manoeuvre beginning at the same 300m/s commences with a turn rate of 37°/s, more than double that of the 8g aircraft. The 20g aircraft then decelerates, more rapidly than the 8g aircraft, being at higher lift and drag, moving up the 20g line, until at the corner speed of 270m/s with a turn rate of 42°/s the stall boundary is met. At this point the aircraft moves down the stall boundary with turn rate decreasing until reaching the same sustained boundary as the 8g aircraft.

The 20g aircraft is therefore capable of significantly greater instantaneous turn rates, but at these rates the higher drag causes a more rapid deceleration. To fully quantify the combat advantage of the 20g aircraft, it is necessary to consider the time required to achieve a given heading change and the accompanying change in speed

2.3 Time to Turn

Table 1 presents a comparison of the time required to complete a 180° heading change for the 8g and 20g capable aircraft of Figure 1.
The first block gives data for a turn at the corner speed. In this case, the aircraft trades height for speed to remain at the corner speed and so complete the turn in the minimum time. The second and third blocks give data for a turn at constant height, with the speed reducing as described above in relation to the turn rate Figure. The second block is for a start speed of 300m/s with the third block giving data for a start speed of 400m/s. The time required to complete the constant height turns was derived using a simple simulation in which inertia terms and pilot response were ignored. For this reason the times will be less than those experienced in actuality, however the data are considered sufficiently representative to permit comparison and identify the trends.

Parameter	8g aircraft	20g aircraft
Corner speed (m/s)	170m/s	270m/s
Turn rate at corner speed (m/s)	26°/s	42°/s
Time for 180° at corner speed	6.9s	4.3s
Time for 180° at constant height, start speed 300m/s	11.5s	5.1s
Speed on completing 180° at constant height, start speed 300m/s	275m/s	165m/s
Time for 180° at constant height, start speed 400m/s	15.0s	5.5s
Speed on completing 180° at constant height, start speed 400m/s	350m/s	250m/s

Table 1 Turn performance comparison

When flying the turn at corner speed, the 20g aircraft possesses the advantages of a higher corner speed, with consequent higher energy, and higher maximum turn rate with obvious effect on time to turn, in this case 2.6 seconds. The attendant disadvantage is that a greater height loss is required to maintain speed due to the higher drag at the higher turn rate.

When flying at constant height from a start speed of 300m/s, the 8g aircraft completes the turn at a speed of 275m/s which Figure 1 shows to be above the corner speed and so permits 8g to be maintained. The 20g aircraft however completes the turn at 165m/s which Figure 1 shows to be below the corner speed. The aircraft has therefore only been able to maintain 20g for a part of the turn, limited by the stall boundary. On completing the turn, the aircraft cannot even achieve 8g.

From the start speed of 400m/s, the 8g aircraft has again been able to maintain 8g throughout the turn. The 20g aircraft completion speed of 250m/s is below the corner speed, but this time on completing the turn it is still capable of 17g.

When flying the turn at constant height, the 20g aircraft completes the turn in less than half the time of the 8g aircraft, but emerges at a lower speed, 60% of that of the 8g aircraft from 300m/s start speed and 70% from 400m/s start speed.

The foregoing analysis shows that a higher structural limit is of benefit in reducing time to turn, but only at dynamic pressures which allow the increased g to be achieved and maintained, in other words where the aircraft is not limited by maximum lift. An aircraft with high structural g limit should therefore also possess a high maximum lift and high maximum speed.

However it is also evident that the speed and hence energy on completion of the manoeuvre will be significantly less than that of a lower structural limit aircraft. In combat terms, the higher g aircraft can gain the opportunity for the first shot, but should that shot not disable the opponent, then the advantage will be lost. Greater thrust will offset the speed decrease, but the consequent mass growth will tend to counter the cost and size advantages of the UCAV.

3 UCAV Structural Analysis

3.2 Evolving the UCAV Layout

In order to provide a comparison with a manned fighter, the UCAV study took the previously designed [3] NGF concept as the starting point. The NGF concept already employed advanced materials, advanced manufacture, low observability and enhanced agility. The final case of [3] quantified the structural design and mass of a NGF aircraft with all these advanced technologies incorporated. The results showed that while retaining the same design mass of 10,000kg, the useful load of the NGF could be increased by a factor of 1.1 compared with that of an equivalent conventional aircraft, together with greater combat effectiveness offered by reduced observability and increased agility. It was assumed that the UCAV would retain the same speed and altitude flight envelope as the NGF, but be structurally capable of 22g instead of 11g.

For the UCAV, the NGF canard and fin structures were accepted. The AMBER method assumes these surfaces to be designed by dynamic pressure and design weight and they are therefore unaffected by change in structure manoeuvre loads.

For the wing, the AMBER NGF model was used with the loading increased to 22g. The internal structure layout was then optimised to give a solution offering minimum mass while providing adequate strength, structural stability and stiffness.

The lessons learned from the previous NGF case studies were applied to proceed quickly to optimum solutions. The NGF wing analysis process set the proportion of moment loads to be resisted by the skin to unity and derived a skin thickness distribution to ensure the retention of acceptable aeroelastic characteristics. Since the UCAV wing will be stronger than that of the NGF, acceptable aeroelastic characteristics for the UCAV will also be retained. The analysis process for the UCAV was therefore as follows:

- Set the proportion of moment reaction taken by the skin to unity.
- Set the skin thickness distribution to that of the NGF (retaining aeroelastic stiffness).
- Derive the skin thickness distribution for strength to withstand 22g.
- If the resulting skin thickness distribution for strength is less than that of the NGF, use the NGF values.
- Add sufficient spars to prevent buckling.

Application of this process did result in the skin thickness of the NGF being retained but with a spar distribution of 11 at the root, 7 at mid-span and 5 at the tip (compared to 9, 6 and 4 for the NGF). The wing mass increased to 472kg per side compared to the 303kg per side for the NGF.

For the fuselage, the AMBER NGF model was again taken as a starting point and the following modifications made :

- The wing mass was modified to that produced by the analysis described above (944kg instead of 606kg),
- The canopy was removed saving 50kg,
- The crew member was removed saving 100kg,
- The ejector seat and cockpit fittings were removed saving 140kg,
- The instruments were removed saving 30kg,
- The air conditioning was removed saving 50kg,
- The pressurisation loads on bulkheads were set to zero,
- Secure datalink avionics were added to the avionic suite adding 100kg, located in what was the cockpit volume

No account was taken of how the volume released by the removal of the crew sub-systems might be utilised (for fuel for example) or how increasing the manoeuvre limit might affect the design and mass of non-structure items.

The AMBER method employs an iterative approach to deriving a design solution. An aircraft balance criteria is used to ensure that the aircraft can be trimmed at the ultimate manoeuvre design case. This facility also determines the wing and tailplane/canard root loads required for trim. These loads are expressed as a proportion of the maximum loads produced from the analysis of these surfaces. Should a proportion be greater than unity, then the loading on that surface must be increased accordingly and the process repeated. If however a proportion is significantly less than unity, then the loading may be reduced with consequent mass saving.

Application of this process to the UCAV required several iterations, the most significant of which involved moving the canards further forward to increase control power while minimising mass penalty. Due to the high lift forces provided by the canard, it proved possible to reduce the overall loading on the 22g wing. Aerodynamic analysis confirmed that the wing and canard could develop the required lift.

Incorporating all the above considerations showed that the fuselage structure mass was 948kg, an increase of 188kg over that of the NGF.

3.3 Planform Layout

With regard to wing and fuselage, the UCAV planform is unchanged from the NGF with the exception of the removed canopy profile. The UCAV canards are of the same size as the NGF, but have moved 2.5m forward. The UCAV layout is illustrated in Figure 2 with the NGF layout for comparison.

The forward location of the control surfaces on the UCAV configuration suggests a missile type layout. This is rational when it is considered that missiles are often designed to be capable of high g manoeuvres during their terminal phase.

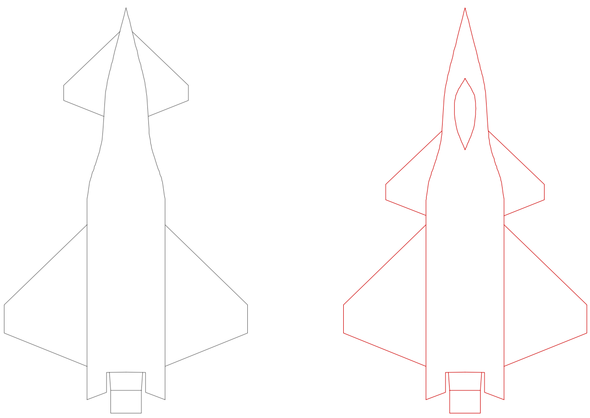

Figure 2 UCAV and NGF Planforms

3.4 Summary of AMBER UCAV Results

The results of the application of the selected UCAV features compared to the NGF are shown in Table 2 for equipment mass and Table 3 for structure mass.

Equipment	NGF mass (kg)	UCAV mass (kg)	Mass change (kg)
Canopy	50	0	-50
Crew	100	0	-100
Ejector seat and cockpit fittings	140	0	-140
Instruments	30	0	-30
Air conditioning	50	0	-50
Secure datalink	0	100	+100
TOTAL			-270

Table 2 UCAV equipment masses

Assembly	11g NGF mass (kg)	22g UCAV mass (kg)	Mass change (kg)
Wings	606	806	+200
Canards	126	126	0
Fin	97	97	0
Fuselage	760	948	+188
Total flight structure	1589	1977	+388

Table 3 UCAV structure mass results

Table 4 shows the values of structure and equipment mass and useful load, the latter modified to maintain the design mass at 10,000kg. The cg position, pitch inertia and peak fuselage shears and moment at the design mass condition are also shown for later comparison with the NGF.

Parameter	Value
Total flight structure mass	1977 kg
Equipment mass	4195 kg
Useful load (fuel plus payload)	3828 kg
cg position aft of first frame at design mass	6.63 m
Pitch inertia at design mass	81,320 kgm^2
Maximum fuselage shears (kN)	181, -350
Maximum fuselage moment (kNm)	540

Table 4 UCAV aircraft values

4 Discussion of Results

4.1 Structure Mass

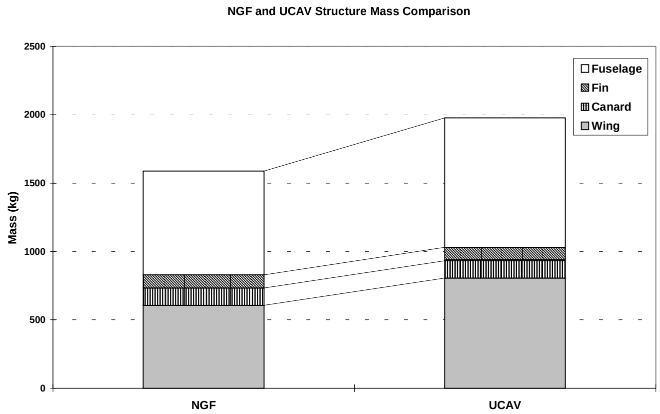

Figure 3 Structure mass breakdown

Figure 3 illustrates the structure mass breakdown for the NGF and UCAV. The fin mass is the same for both concepts since it is assumed that the fin is not affected by the increased structure manoeuvre limit. The canard mass is also unchanged because the balance analysis showed that by moving the canard forward, the required trim moment could be provided without increasing canard loading. With the doubling of the manoeuvre limit the mass of both the wing and fuselage increase significantly (by 33% and 25% respectively). The increase in structural mass is not linear with g partly by minimum gauge criteria and partly due to the increased contribution to lift of the canard. This allows the 22g UCAV wing loading to be less than twice that of the 11g NGF wing.

The wing leading edge mass increased from 42kg to 56kg. This is due to higher aerodynamic loading requiring strengthened attachments and to an increased number of ribs (from 10 to 13) to avoid skin buckling. The leading edge skin mass is unchanged since it is sized by birdstrike requirements.

The wing trailing edge mass increased from 53kg for the NGF to 84kg for the UCAV. The mass of all the trailing edge components increased, with the largest increase coming from the attachments. The number of ribs increased from 25 to 32 and the local skin reinforcement thickness for the attachments increased from 5.7mm to 7.8mm whereas the basic skin thickness remained at the 2.0mm minimum gauge for carbon fibre.

The wing torque box mass increased from 208kg for the NGF to 263kg for the UCAV. Again, the mass of all the box components increased, but in this case the largest increase came from the ribs. The basic skin thickness distribution is the same for both aircraft to take account of aeroelastic requirements, however the UCAV has thicker local reinforcement at the attachments (11.0mm compared to 8.5mm for the NGF). As previously reported, the number of wing spars was increased for the UCAV.

The fuselage structure mass increased from 760kg for the NGF to 948kg for the UCAV. As the skin thickness was selected by minimum gauge the skin mass remained unchanged. The mass of main frames increased due to the higher point loads from the wing. The mass of intercostal frames increased due to the higher shear force distribution. The mass of longerons increased due to the higher bending moments from the canard attachments in the forward fuselage. The bulkhead mass reduced slightly due to the removal of the pressurisation loads.

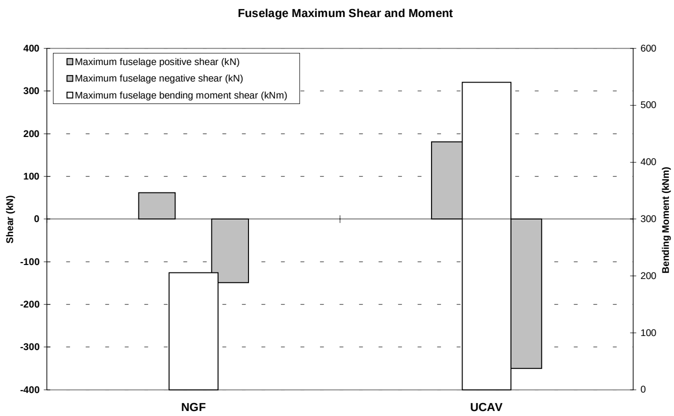

Figure 4 Fuselage maximum shear and moment

As an example of the degree of detail provided by the AMBER method, Figure 4 shows the peak values of fuselage shear force and bending moment. It can be seen that for the 11g NGF, the maximum shear is approximately 150kN and the maximum moment is approximately 205kNm. The 22g UCAV, with the more forward canards, has a maximum shear of approximately 350kN and a maximum moment of approximately 540kNm. The loads have more than doubled due to the forward movement of the canard. This is structurally less optimum than the NGF canard location. Also there is less load alleviation due to fuselage mass distribution for the UCAV compared to the NGF.

Figure 5 shows the shear and moment distribution for the NGF. In [3] it was noted that this distribution was structurally efficient, with the shear distribution crossing the zero axis 5 times, substantially reducing the magnitude of maximum shear and moment compared to the classical distribution in which the shear typically crosses once.

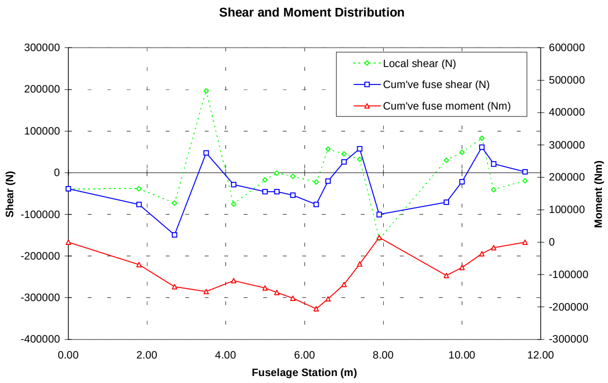

Figure 5 NGF fuselage shear and moment distribution

Figure 6 shows the corresponding distribution for the UCAV. The multiple crossing distribution is retained, but with fewer intersections. It is evident how the magnitudes of the UCAV distributions have increased.

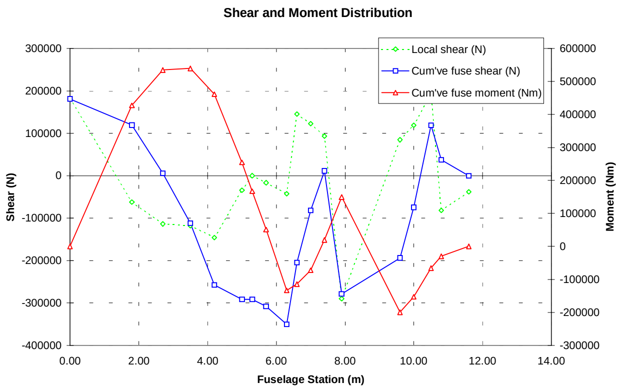

Figure 6 UCAV fuselage shear and moment distribution

4.2 Equipment Mass and Useful Load

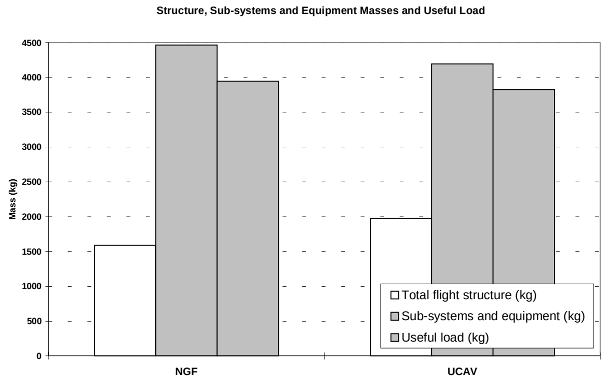

Figure 7 Structure, equipment masses and useful load

Figure 7 shows the structure and equipment masses and useful load. The UCAV structure mass increase of 388kg is largely offset by the saving of 270kg in equipment to give a decrease of 118kg in useful load, or just 3%.

4.3 Design Mass Breakdown

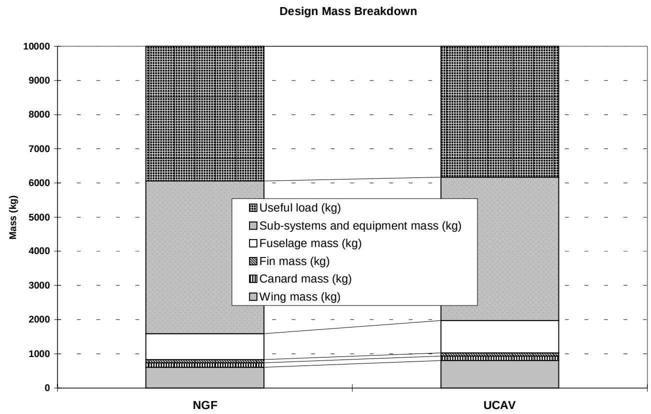

Figure 8 Design mass breakdown

Figure 8 shows the breakdown of the design mass into the masses of wing, canard, fin, fuselage (from Figure 6), equipment and useful load (from Figure 10) for both the NGF and UCAV. The Figure illustrates the countering effects of structure mass increase and equipment mass decrease for the UCAV to give little change to useful load. However the reduction in useful load (stores and fuel) will reduce the payload-range capability of the UCAV.

4.4 Pitch Inertia and cg Position

The pitch inertia and centre of gravity (cg) position at the design mass of 10,000kg were also considered in the case study and these are illustrated in Figure 9.

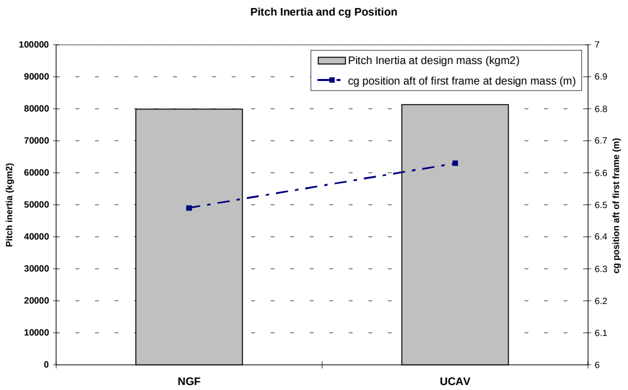

Figure 9 Pitch inertia and cg position

The UCAV has a slightly increased pitch inertia (of 2%) due to the forward movement of the canard and aft movement of the cg (by 0.14m). The latter is due to the removed crew sub-systems and equipment (saving 270kg) most of which were located forward at what used to be the cockpit, overcoming the effect of the forward movement of the canard (of mass 126kg). For the UCAV, the aft movement of the cg position compared to the NGF is accompanied by a movement forward of the neutral point due to the forward canard movement requiring re-assessment of the stability and control of the aircraft. These relative movements of cg and neutral point will result in a decrease in static stability which may well be desirable for an agile UCAV.

5 Conclusions

1. This paper has presented the application of the AMBER design based structural mass prediction method to a UCAV concept. The analytical basis of the method has been used to quantify the effect on structural design and mass properties of technologies suited to the UCAV.
2. The study has shown the concept to be feasible in that the UCAV is capable of generating and withstanding the required accelerations. These accelerations bestow significantly improved turn rates compared to a manned fighter.
3. The structure and planform layouts have been derived and the mass breakdown predicted. Holding the design mass at the same value as the NGF resulted in a small (3%) reduction in useful load for the UCAV. This is because the gain in structure mass was greater than the saving in equipment mass.
4. The detail given by the study results demonstrate the deeper insights into the design of the structural framework and the far greater confidence given by AMBER compared to statistically based methods. This is because such methods require a well-populated database from which to derive mass estimating relationships. Further, statistical methods are unable to address fundamental characteristics of new concepts, such as the canard and wing loads and fuselage inertia interaction of the UCAV.
5. From the results of this and other studies, together with favourable evaluation by UK and US research organisations, it is concluded that the AMBER method is a valuable technique in the design of future innovative aircraft concepts.

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