ISSN 1648-7788 AVIATION, Vol IX, No 2, 2005

PROCEEDINGS OF THE SIXTH INTERNATIONAL SEMINAR ON
*"Recent Research and Design Progress in Aeronautical Engineering
and its Influence on Education"* – Riga, Latvia

CIVILIAN LONG ENDURANCE UAV – DESIGN CHALLENGES

Z. Goraj

Warsaw University of Technology, Warsaw, Poland. E-mail: goraj@meil.pw.edu.pl
Received 04 04 2005, accepted 10 06 2005

Zdobyslaw GORAJ, Prof
Education: MSc (Eng.) - 1972, PhD - 1977, D Sc - 1992, Prof – 2002.
Affiliations and functions: 1973 – 2002 - Warsaw University of Technology, Lecturer of Flight Dynamics; 1982 – 1989 - Light Aircraft Company PZL - Okecie - Senior Airplane Designer; 1992 – 1999 - Institute of Aviation - Head of Flight Dynamics Group; 1993 – 1996 - Institute of Aeronautics and Applied Mechanics - Deputy Director; 1996-2002 - Vice Dean for Scientific Affairs at the Faculty of Power and Aeronautical Engineering.
Experience: Aircraft Designer since 1982; Flight Dynamics Researcher since 1977; Main Organizer of the International Seminars entitled: „Recent Research And Design Progress In Aeronautical Engineering And Its Influence On Education" (1994-2000); Member of Editorial Boards of the following Journals: (1) Aircraft Design (Holland) (2) Journal of Aerospace Engineering (United Kingdom) (3) Turbo And Jet-Engines (Israel) (4) Transactions of the Institute of Aviation - Scientific Quarterly (Poland); Polish Coordinator And Representative in European Fifth Framework Program devoted to Unmanned Aerial Vehicles – Coordinator of UAVNET And CAPECON projects;
Lectures in Foreign Institutions: 1997 - Kyushu University, Japan, Long Endurance High Altitude Unmanned Aerial Vehicles; 1998 - Bristol University – UK, Panel methods in teaching of airplane design; 1999 - Saint-Cyr – France, Panel methods - theory and practice; Old Dominion University, Virginia, USA; Coupled Flight Dynamic / Panel Method Tool for Conceptual Design And Analysis of Existing Vehicles; 2000 - Boeing - Saint Louis, USA, Coupled Flight Dynamic / Panel Method Analysis; Israel Aircraft Industry, Design and Flight Dynamics of a HALE UAV; 2001 - London, Kingston University, Civil Unmanned Aerial Vehicles (UAVs) "State of the Art And Challenges for the Future.
Teaching: Mechanics of Rigid Bodies, Flight Mechanics, Flight Dynamics, Airplane Aerodynamics and Airplane Design.
Publications: Author of numerous journal and conference papers (more than 80).
Present position: Head of Department of Airplane And Helicopter Design; Course Director for Aerospace Engineering Program in WUT.

Abstract. This paper presents a selected aspect of design activity devoted to optimising HALE and MALE UAVs. The project is taking place at Warsaw University of Technology under the V Framework of European Union in the CAPECON project. This paper deals with wing airfoil selection, defining of the configuration layout and power unit integration. A brief overview of wing sections developed in some design centres (mainly in Israel Aircraft Industry and in Northrop Grumman) is included. Aircraft layout depends on the mission and sensor selection and is discussed using the examples of PW-103 and PW-114. Engine suspension and integration with aircraft is included in the analysis because if it is not properly analysed, it can lead to an excessive vibration and fatigue of the whole aircraft structure.

Keywords: Unmanned Aerial Vehicles, aircraft design, engine suspension.

Notations

Acronims

BWB	Blended Wing Body
FLIR	Forward Looking Infra Red
HALE	High Altitude Long Endurance
SATCOM	Satellite Communications
MAC	Mean Aerodynamic Chord
SAR	Synthetic Aperture Radar
UAV	Unmanned Aerial Vehicle

Symbols

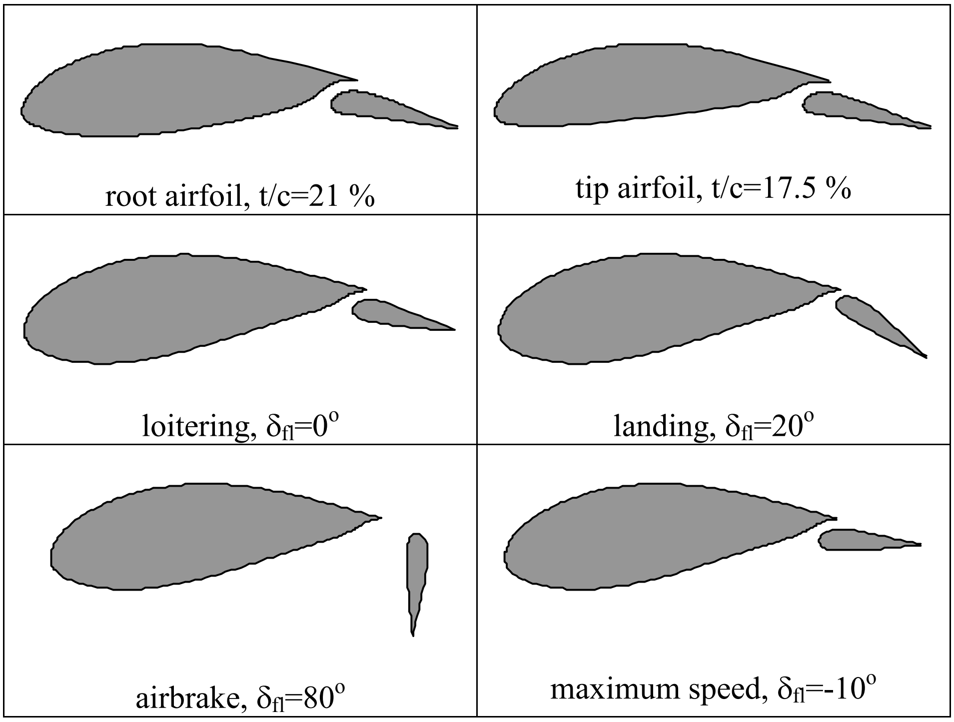
a, a_1	lift curve slope for main wing and canard, respectively
c_a	value of MAC
C_L	lift coefficient
$C_{L\,max}$	maximum lift coefficient
C_m	pitching moment coefficient about point of 25% of MAC
l_C	arm of canard with respect to point A=25% of MAC
Ma	Mach number
Re	Reynolds number
S	wing gross area
S_c	canard gross area
t/c	airfoil thickness
α	angle of attack
δ_F	elevon deflection (positive if TE goes down)
δ_{fl}	flap deflection (positive if TE goes down)

Introduction

There are many who believe that long range unmanned aerial vehicles will be routinely operated in the civilian sector in 10 years time. This can be achieved only if the platforms of future UAVs are economically competitive, safe, and reliable. Rapid progress in aeronautical technology is an optimistic promise that if it could be done very soon. This paper accentuates some universal aspects and features of all aerospace designs, namely design, new materials, safety, reliability, cost, and economic competitiveness. An effort undertaken at Warsaw University of Technology to design a number of platforms able to fulfil these very demanding requirements for future UAVs will be shown. A special emphasis will be put on selecting the platform best suited for the planned mission. The trade-off between aerodynamic efficiency, performance, flight stability, selection of the flight control system, payload and sensor volume, reliability, and safety will be reviewed.

1. Aerodynamic design

Long Endurance UAVs are very demanding with respect to airfoils and wing geometry, especially those of High Altitude (HA). It is usually impractical to use directly the well-known types of wing sections. High loitering lift coefficient provides very demanding requirement about maximum lift. Moreover, relatively thick airfoils generate a high negative pitching moment, which has to be trimmed by deflected up elevens (in case of flying wings) or by deflected up elevators (in the case of classical configuration). From the other side, CFD commercial codes available today make it possible to develop a mission-tailored, customized wing for any new UAV. Many such mission-oriented wing sections have been developed at IAI within the last 25 years [5, 7 - 9]. Among them there are high-lift Natural Laminar Flow (NLF) sections, either as single or two-element wing sections (HASA – High Altitude Slotted Airfoil), Fig 1. Many of these airfoils were developed using MSES code [1].



root airfoil, t/c=21 %

tip airfoil, t/c=17.5 %

loitering, $\delta_{fl}=0^o$

landing, $\delta_{fl}=20^o$

airbrake, $\delta_{fl}=80^o$

maximum speed, $\delta_{fl}=-10^o$

Fig 1. Mission-adaptive FT/EX wing section, from [2]

This was followed by a number of subsonic and transonic wings, including LRT_17.5 (Low Reynolds Transonic), TLD_0.65/15A (Transonic Loitering Double) and the three-element airfoil DSA/EX (Double Slotted Airfoil / Extended Lift Range) designed for STOL UAV configuration [9, 7].

The HALE UAV configuration designed at Warsaw University of Technology received the LRT_17.5 airfoil. The reason for this is that the ceiling parameter ($Ma^2C_{L\ max}$) of the PW-114 HALE UAV is 0.55, i.e. the same as the value of the LRT_17.5 airfoil. Assuming that the loitering Mach number is equal to 0.6, one obtains $C_{L\ max}$ equal to 1.52. However, a disadvantage of the LRT airfoil is its high negative pitching moment (of order –0.22) and high negative hinge moment (of order –0.30). The geometry of the LRT_17.5, compared to the Global Hawk airfoil, is shown in Fig 2.

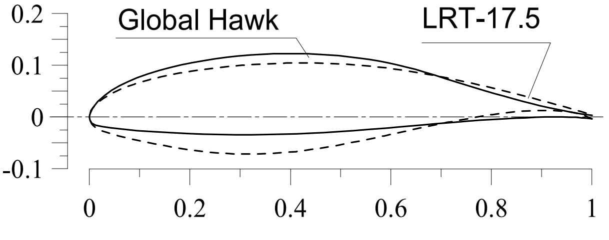


Fig 2. LRT and GH wing sections (GH airfoil geometry was not authorized by Northrop Grumman)

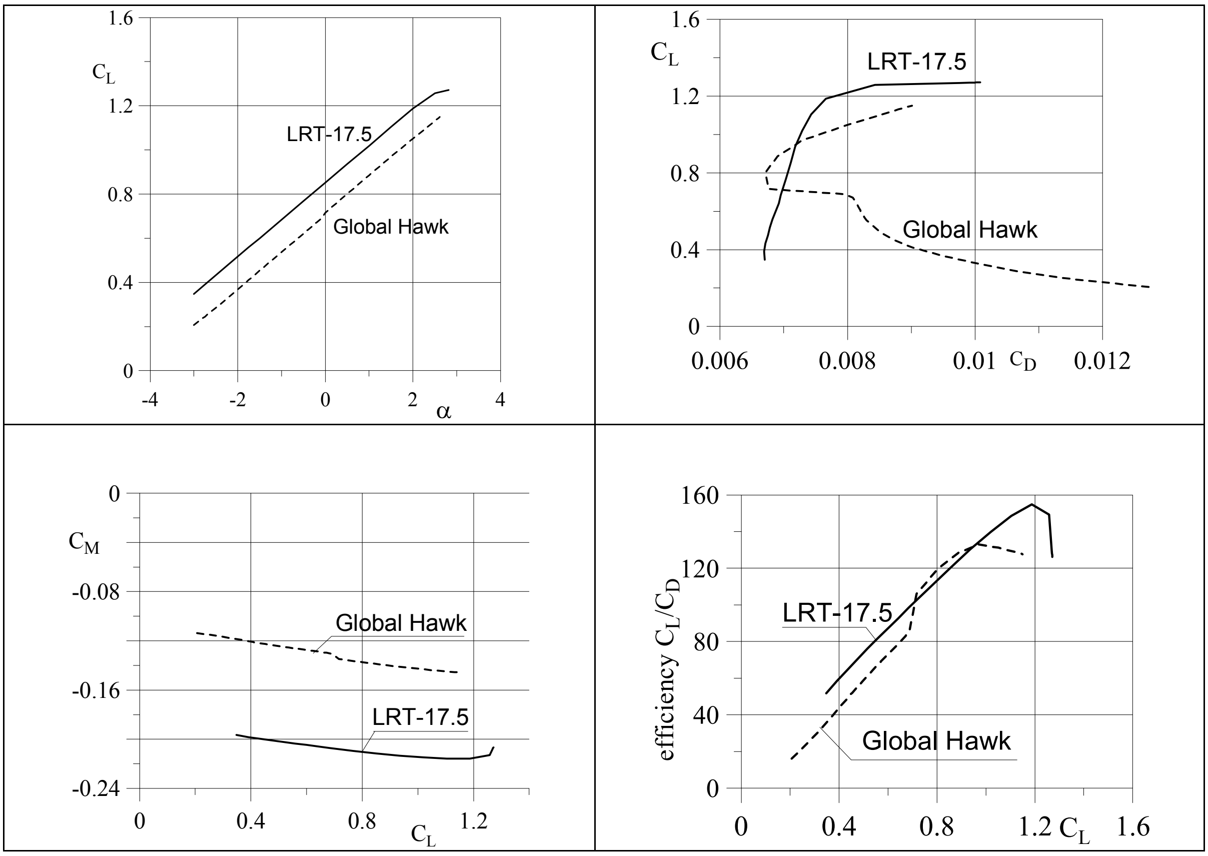


Fig 3. Selected parameters computed for LRT and GH airfoils using MSES code [6]. Re=1.5E6, Ma=0.6

A new UAV design process will be shortly discussed based on experience gained during the development of PW-114 – a HALE class UAV (Fig 4-5) [4, 3, 2]. Configuration called as the PW-111 was assumed as a starting point. It was a Canard configuration, selected for its high longitudinal manoeuvrability. A vertical stabilizer was located under the rear part of the centre wing. However, it appeared that such a configuration is also heavily unstable in pitch [4]. To improve longitudinal dynamic stability, the configuration of PW-111 was redesigned and a new configuration called PW-112 was designed. The main difference between PW-111 and PW-112 was due to shifting the Canard backward. However, a numerical stability analysis showed that PW-112 was still unstable. A corresponding theoretical analysis was performed and its main results are presented in Fig 6. This figure shows that independently on the canard area S_C and its lift curve-slope a_1 the natural longitudinal stability can be attained when the dimensionless arm L_H/c_a is negative, i.e. when the canard is replaced with a classical tail plane. This result is consistent with a traditional way to improve a longitudinal instability – stability can be improved either by shifting the centre of gravity forward or by using a fly-by-wire system able to deliver an artificial longitudinal stability. However, in the case of PW-111, both these remedies could not be used. The first solution was not applicable because the nose part of the fuselage had to be used as a container for the main sensors and the communication suite: SAR, FLIR and SATCOM. Artificial stability also could not be accepted because of its cost – a preliminary assumption was that airplane would be as cheap as possible.

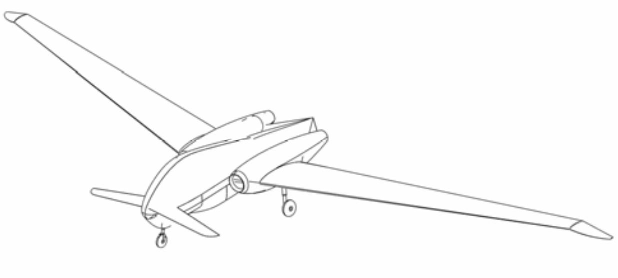


Fig 4. PW-111 as a starting point to new HALE UAV [4]

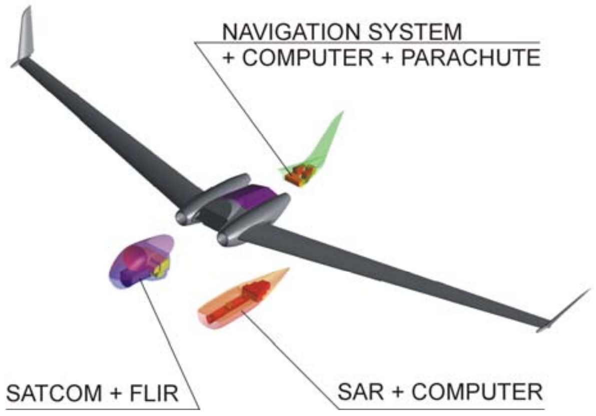


Fig 5. Design process usually starts when payload and its distribution over configuration is preliminarily defined

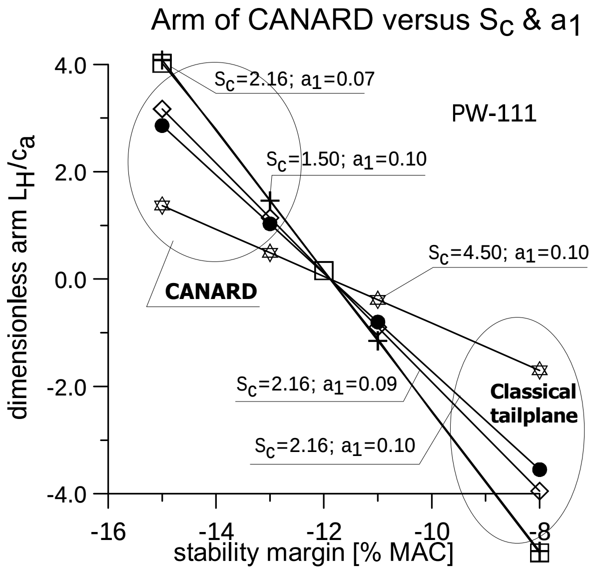


Fig 6. Influence of the Canard parameters on the HALE PW-111 longitudinal stability

The next step in the design process of the HALE UAV was a configuration called PW-113. This was a Blended-Wing-Body (BWB) configuration, for which the longitudinal trim was attained by symmetrical deflection of wing tip elevens (combination of elevators and ailerons). The main differences between the PW-112 and PW-113 configurations include:

- Increasing wing span

Increasing wingspan is the consequence of decreasing wing loading and the required lift coefficient. The lift coefficient required for the high altitude flight at Ma=0.6 was decreased from 1.4 to 0.9. To have the same aspect ratio the span was increased from 24 m to 28 m. The taper ratio was increased from λ=0.5/1.973=0,25 to λ=0.7/1,973=0,35. Increasing both the taper ratio and the tip chord was necessary because elevens, not by canard, now perform the longitudinal control.

- Changing the shape of the body

The shape of the body was changed to have the pressure distribution, which is able to reduce the overall negative pitching moment. Shifting up the reward part of the fuselage did it. At the same time, the shortening the front part of the fuselage resulted in improving lateral static and dynamic stability.

- Increasing the vertical stabilizer

Increasing the vertical stabilizer was necessary to improve lateral static and dynamic stability.

- Longitudinal and lateral control

Because PW113 is a pure Blended Wing, all control functions are performed by surfaces placed on the wing. Control surfaces are located along the wingspan in main three zones: (1) trim flaps; (2) air brakes; and (3) elevens.

(1) Trim flaps

This surface is intended to change pressure distribution versus span. The intention is to increase lift over the inboard part of the wing, to decrease lift over the outboard part of lift, and decrease the bending moment as fuel weight decreases.

(2) Airbrakes

Airbrakes are used to control the aircraft laterally. Flap is divided and can be deflected either jointly (up or down) as classical flap or trimmer or separately (up and down) as airbrake.

(3) Elevens

With respect to design and function the elevens are similar to trim flaps. They can be deflected either in the same direction on left and right wing (up or down) as classical elevator, or differentially (up and down or down and up) as classical ailerons.

2. Configuration Layout

There is a difference between low and medium altitude unmanned flights from one side, and high altitude flights from the other sides. Propeller propulsion systems are the best choice at low and medium altitudes, whereas turbofan engines of modest bypass ratio with acceptable thrust loss are preferred choice at high altitudes. In both cases, the nose of the fuselage usually houses a variety of different sensors and a typical design process starts from the nose equipment bays. Sometimes such equipment is desirable to be quickly exchanged, so a modular configuration is a natural choice. Today SATCOM seems to be a standard communication suite for HALE configuration, whereas it could be an option for the MALE configuration (most MALEs still have LOS antennas as the only communication solution). In the MALE class, one can observe a two-beam layout, empennage located behind straight wing, and pushing propeller as a dominating configuration. The reason for this is explained in Fig 7.

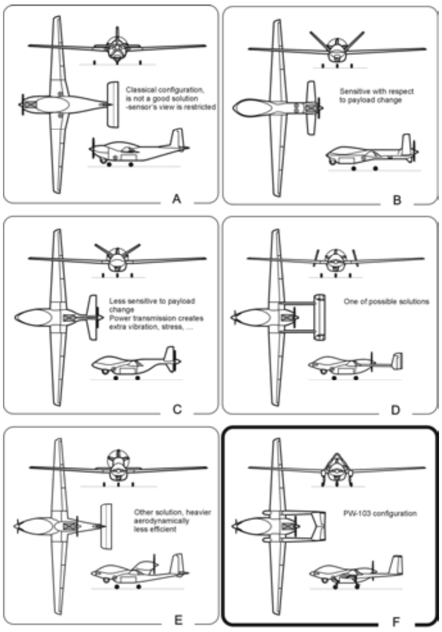


Fig 7. Selected number of MALE layouts – from typical general aviation (A) to two-beam UAV with pushing propeller (F); Configurations B, C, D, E, F have an small auxiliary engine with pulling propeller, which does not restrict view of sensors

The twin-boom, pushing main power unit selected for MALE configuration offers high mission flexibility (payload can be quickly and easy exchanged without extensive influence on stability and manoeuvrability). Emergency power also increases the safety level (in an emergency due to main engine failure, the auxiliary power unit is activated and the aircraft is able to return home safely). It is an additional cheap, low weight of order 15 kg, multi-fuel engine, often used by flying targets as the main power unit (for example model AR 731 of 38 hp and 7800 rpm), preferably a rotary piston engine. Two-blade, feathered propeller in tractor configuration is placed at the nose of fuselage. Wing loading was chosen in order to have good endurance, rate of climb short take-off and to be relatively insensitive to gust. A diesel engine and five blade propeller was selected because of very low SFC (8.8 l/h @ 0.4 PNOM & 18.5 l/h @ 0.6 PNOM). The silhouette of the airplane results from the placement of antennas, SAR, FLIR, etc. and their undisturbed fields of vision. The light structure weight was obtained by using honeycomb sandwich and graphite rowing. All on-board safety related systems are doubled or three-fold redundant.

3. Engine Suspension

Turbofan engines, prepared to be attached to airplane structures using a number of screws, usually power HALE UAVs. For FJ-44, four screws attach to each of two settings, Fig 8. Adjustment of engine attitude can be performed using the so-called adjusting nuts (Fig 9, 10). Maximum amplitude of horizontal shift (measured at the plane of clamping ring, Fig 9, 10) is equal to 34 mm and corresponds to engine angular rotation (in the horizontal plane) equal to 3.8^{o}. Maximum amplitude of vertical shift (measured at the plane of the clamping ring, Fig 9) is equal to 53 mm and corresponds to engine angular rotation (in the vertical plane) equal to 5.9^{o}. Engine suspended over aircraft structure excites vibration, usually at the frequencies corresponding to shaft rotation (for FJ-44, the shaft angular velocity is equal to 12,500 rpm). An elastic tube shell (pointed at with an arrow at left part of Fig 9) damps vibration. To analyze the state of displacement, strain, and stress and to compute the natural vibration in various structural components of complicated geometry, the classical finite element method was used. External forces acting on the structure were assumed selecting a type of maneuver and it basing on FAR-23. Fig 11 shows forces acting on the engine front seating during a pullout maneuver. Mesh generated over the engine front seating is shown at Fig 12. Modes of vibration computed for adjusting screw using ANSYS system are shown at Fig 13. Such analysis usually includes many different critical cases defined in FAR-23 and has to be performed for all elements of loading structure. Usually it is very laborious task, but it must be done to optimize the aircraft structure and decrease its weight.

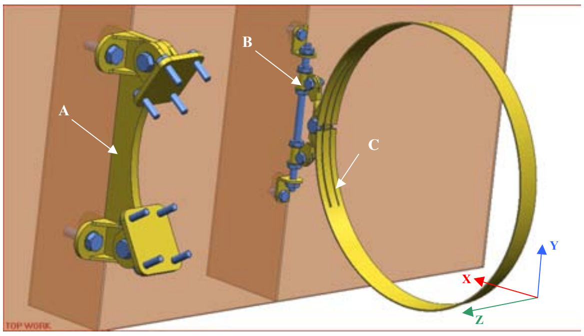


Fig 8. FJ-44 turbofan engine is suspended to the airframe of PW-114 aircraft in 3 points: each of front seating is joined to a vertical beam (A) through a horizontal pin; clamping ring (C) is attached to the vertical adjusting nut (B) [10]

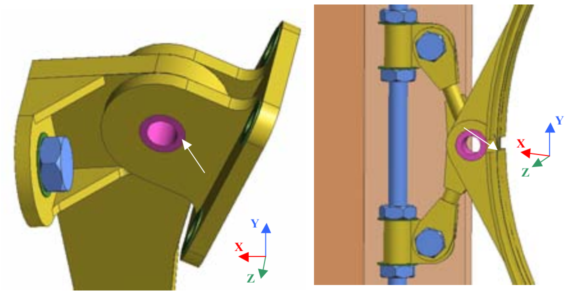
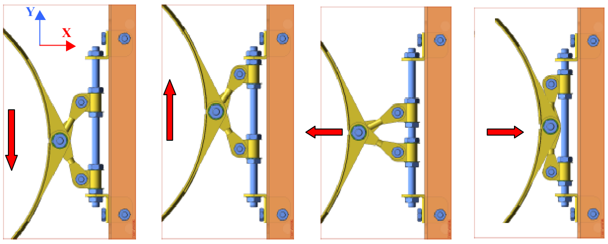


Fig 9. Details of suspension system: the front seating (left) is adjusted to engine geometry; the rear-clamping ring (right) can be regulated and shifted both in vertical and horizontal directions [10]



a b c d

Fig 10. Rear clamping ring can be shifted either vertically if both adjusting nuts are moved asymmetrically (a, b) or horizontally if both adjusting nuts are moved symmetrically (c, d), [10]

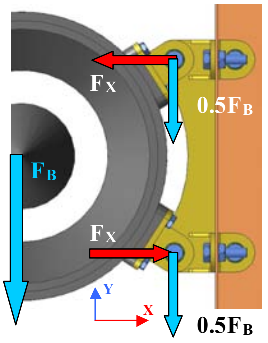


Fig 11. Selected forces acting on the engine front seating during pullout maneuver [10]

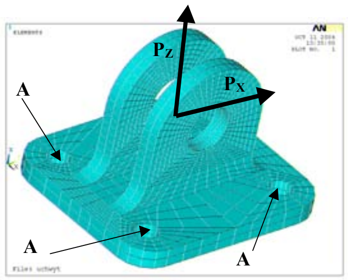


Fig 12. Mesh generated over the engine front seating for Finite Element Analysis [10]

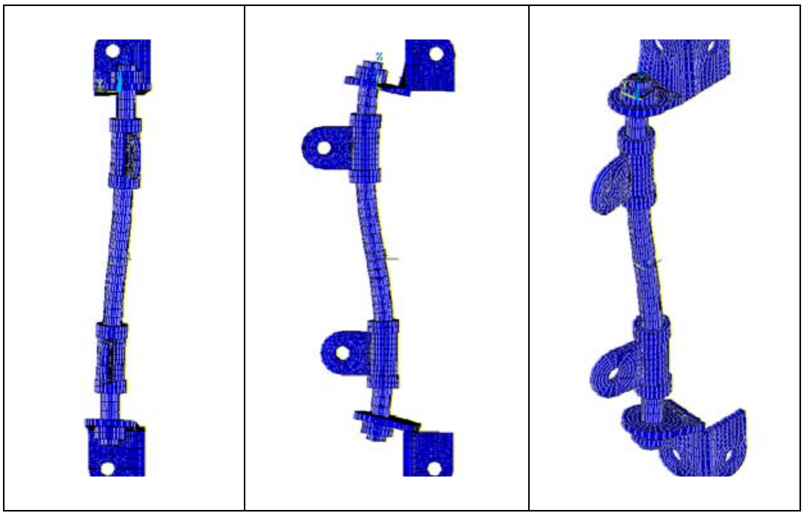


Fig 13. Modes of vibration computed for adjusting screw using ANSYS system [10

The integration of the diesel engine with the MALE UAV structure is not a trivial task. Only a few certified diesel engines are available on the market, and all of them were designed for the automotive industry. A Centurion 1.7 (the former Thielert Diesel Engine developed by Mercedes) was selected as the main power unit for the PW-103 UAV. It was originally adjusted for asymmetrical three-point suspension to a car's loading structure. This asymmetrical suspension system (Fig 14) causes serious trouble when the engine is to be attached to an aircraft airframe. The Centurion 1.7 engine was attached to the aircraft airframe at five points through a space truss made of steel pipes. The arrangement of the steel pipes is strictly limited by the height of the aircraft fuselage, the engine accessories, and asymmetrically located points of engine attachment. Static and dynamic truss loading, stress, strain, and the frequency of the natural vibration of the engine assembly were computed numerically using ANSYS software based on Finite Elements Methods. The engine body was modeled as a non-elastic (stiff) element of assumed weight and moments of inertia, Fig 15. The static strength of the space truss is sufficient, but eigenfrequencies are relatively low, see Table.

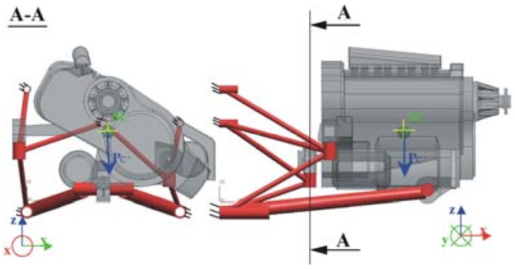


Fig 14. Diesel engine (Centurion 1.7) developed by automotive industry and originally adjusted for asymmetrical three-point suspension to car loading structure. This asymmetrical suspension system makes serious troubles when engine is to be attached to an aircraft airframe [6]

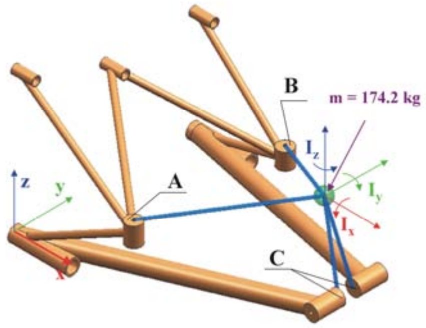


Fig 15. Diesel engine was attached to the aircraft airframe at five points through a space truss made of steel pipes. Engine body was modeled as non-elastic (stiff) element of assumed weight and moments of inertia [6]

Table. The first ten eigenfrequencies computed for rigid body engine suspended to stiff airframe through elastic space truss

Mode number	Frequency ω [$^{rad}/_{s}$]
1	34.44
2	71.92
3	115.00
4	142.74
5	271.73
6	349.91
7	379.07
8	381.59
9	385.41
10	389.60

The engine operating frequency is equal to 261 rd/s and this means that during start-up, the forced frequency crosses the natural frequencies of the engine assembly four times. Usually it excites the excessive amplitudes and accelerates the fatigue of the aircraft structure. Actually, a redesign process started to increase suspension stiffness and to shift all eigenfrequencies beyond the engine operating frequency. Generally speaking, external forces will be introduced to the engine body through an extra ring attached to the engine body at plane AA (Fig 14).

Conclusion

Competitiveness (dependent on low acquisition cost and low direct operating cost), safety and reliability will decide if UAVs are routinely operated in civilian missions in the coming years. Carefully selected wing sections, adjusted to the mission, a general aircraft layout, and power unit selection are the key parameters influencing competitiveness. For a HALE UAV, a good solution is a BWB configuration of a high aspect ratio wing with an inherent low wetted area, powered by a turbofan engine. For a MALE UAV, a diesel engine seems to be a good solution. However, diesel engines today are not adjusted enough to be integrated with airframe structure and a special ring has to be designed to transfer reaction forces from the engine body to the airframe. The goal is to increase suspension stiffness and shift all eigenfrequencies to much higher values, i.e. beyond the engine body operating frequency.

References

1. **Drela M**. A User's Guide to MSES V2.6"/ MIT Computational Aerospace Laboratory. – 1994 May.
2. **Goraj Z., Frydrychewicz A.** Development approach of the PW–103 – an increased reliability MALE UAV – under the CAPECON project within the V FR of EU // ICAS Congress 2004, Japan, Yokohama. 2004. – Paper 1–6–R2.
3. **Goraj Z., Frydrychewicz A. Hermetz J. et al.** HALE UAV platform optimised for a specialized 20-km altitude patrol mission // Ibido. Paper 1–6–3.
4. **Goraj Z., Frydrychewicz A., Świtkiewicz R. et al.** High altitude long endurance unmanned aerial vehicle of a new generation – a design challenge for a low cost, reliable and high performance aircraft // Bulletin of the Polish Academy of Sciences. – 2004. – Vol 52, No 3. – P. 173–194.
5. **Koss D., Steinbuch M., Shepshelovich M.** Development of two-element NLF airfoils for long endurance flight // 35th Aerospace Sciences Meeting and Exhibit, January 6–10, 1997, Reno, NV, AIAA 97-0514.
6. **Maziarz M.** Suspension of Diesel Engine in PW-103 UAV: M.Sc. Thesis at Warsaw University of Technology. – Warsaw, 2005 /unpublished.
7. **Shepshelovich M.** Aerodynamic Concept Of IAI Long Endurance UAV // 44th Israel Annual Conference On Aerospace Sciences, 25-26 Feb. 2004, Ben-Gurion Airport, 70100 Israel.
8. **Steinbuch M., Marcus, B., Shepshelovich M.** Development of UAV Wings – Subsonic Designs'// 41st Aerospace Sciences Meeting and Exhibit, Reno, NV, 6–9 January 2003.
9. **Steinbuch M., Shepshelovich**, **M**. Development of High Altitude Long Endurance Airfoils // 42nd Aerospace Sciences Meeting and Exhibit, Reno, NV, 5–8 January 2004.
10. **Sutor B.** Static and dynamic analysis of engine suspension in PW-114 UAV: M.Sc. Thesis at Warsaw University of Technology. – Warsaw, 2004 /unpublished.