



ON THE EXISTENCE OF A FAMILY OF IDEAL AIRCRAFT CONFIGURATIONS

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Abstract

The bulk of fossil fuel in aviation is consumed in the domain of fixed-wing subsonic flight. Environmental concerns put strong incentives on the industry to improve flight efficiency. Best flight efficiency can only be attained if an aircraft design is based on its ideal configuration. Already since the middle of the previous century, the industry became entrenched in the tube-and-wings configuration, here referred to as the Current Dominant Configuration (CDC). It is widely speculated that better arrangements of wings and bodies exist, and many research initiatives are dedicated to the exploration of alternatives. These are typically done for specific types of aircraft, mostly for the airline industry. Yet, new aircraft developments keep employing the CDC as if proposed alternatives are ignored. Here a hypothesis is tested which suggests that a single family of aircraft configurations exists which is ideal for the majority of economically significant flight objectives within this domain. To organise the aircraft design space into families of configurations, a hypothetical Ideal Wing is introduced as a common basis from which all configurations evolve by inflation to provide practical flyers with volume for their payload. While the most prominent configurations, including the CDC, appear to disqualify as candidates for the proposed ideal configuration, the one which qualifies, has not been seriously examined in human aviation, although it is familiar. Termed the Natural Dominant Configuration, as it appears in natural flyers, it certainly merits further exploration.

Keywords: Aircraft configurations, ideal wing, gull-wing, inflation factor, flight objective.

1. Introduction

Given a coherent design specification, the most critical choice in the process of aircraft design is the selection of the aircraft configuration. If the selected configuration is not ideal for the principal flight duty, no effort of design refinement can ever converge onto the optimum solution. Therefore, it is still common practice during the development of new aircraft to invest extensively towards this choice [1, 2]. The substantial potential economic benefit, which even a slightly superior solution would offer over the entire operational life of all derived aircraft in service, readily justifies the risk of such investments. On the other hand, such investments are futile if a configuration, better than the current best, does not exist. For almost a century, a single configuration has dominated and defined the aviation industry. Explorations of alternatives have received prominent attention throughout the history of aviation, spurred by the suspicion that better solutions must exist. The epoch of the last half century gives the highest priority to flight efficiency and renewed, multi-national investigations of alternatives [3, 4] suggest that consensus is still lacking on the oldest question in aviation: what should an aircraft look like?

A common opinion holds that there is no such thing as a single set of best practices, even at the configuration level. It is argued that the best solution depends on the complex array of priorities of diverse objectives. Different priorities and objectives will render different configurations as ideal. How many ideal configurations are there then? Are the objectives sufficiently diverse that their differences influence even the general arrangement of an airframe? Is there not sufficient commonality within the arrays of objectives that common constituents would be necessary for the solution at the configuration level?

In the early days of aviation, a large diversity of configurations was contesting in competitions, in the early marketplace and in war and in this way the current dominant configuration became firmly entrenched through actual demonstration of superiority. Challenges never ceased but later much was left to desktop studies where it is typical to rank alternatives by means of conceptual comparative studies for specific applications [2, 5]. It is then not surprising that deductions from such isolated comparisons can be inconclusive and provisory, given the complex interdependencies, the huge variety of unconsidered options and the lack of actual implementation. Without taking a design through its full life cycle, including refinement in subsequent generations based on operational experience, no truly conclusive comparative evidence can emerge. It is also impractical to test alternatives across a large spectrum of implementations. Furthermore, theoretical comparisons are mostly done on concepts for large transport aircraft, the sector of the industry, which is most reluctant to depart from well-established, reliable solutions. Although the most significant impact of improvement would come from implementation in the airline industry itself, this sector will remain hesitant to go beyond theoretical exploration to venture into actual implementation due to risk and regulatory constraints. It may therefore be up to other parties within the aviation sector to lead such initiatives.

With flight efficiency now the highest priority in aircraft development, the art of multi-disciplinary optimisation has reached a high level of maturity [6]. It may however be noted that many such optimization exercises still operate within explicit configuration constraints, so that the entire configuration space is not reachable in every search. The focus is often on complex trade-offs and refinement of details within a given configuration and optimal selection at the configuration level remains beyond the repertoire of the typical optimisation tool [7]. With case studies inconclusive, rigorous implementation impractical and optimisation tools not ready for the holistic exploration, a more fundamental approach is needed to progress in this important search.

In this work, we organise the aircraft design space into a family tree of configurations as if all configurations evolved from a common ancestor, a hypothetical ideal wing, over several imagined developmental steps. At every step, several options exist to spawn a diversity of configurational families with identifiable relationships. The last step considered requires a strategy of inflation to yield practical aircraft with sufficient volume for their payload [8].

When mapping any past, existing, or planned aircraft design into this tree of configurations we find the majority of designs assigned to the family of the CDC. This supports the notion that a single family can be suitable for the majority of flight objectives. Interpretation of the relationships in the map also offers explanations as to why some configurations are not generally suitable and therefore fail to be candidates for a dominant configuration. Most importantly, the map reveals another configuration that is generally suitable across the scope of inflation. Yet this configuration has not been properly explored as a candidate in human aviation.

Not only could this configuration be generally applicable in human aviation, but it is also expected to be superior to the CDC and, in fact, it is already the dominant configuration in the domain under consideration among the natural flyers. We therefore call it the natural dominant configuration (NDC) or the gull-wing configuration, owing to the characteristic fore-aft sweep and polyhedral of the wings. This makes it a convincing candidate to be considered the ideal configuration as one would expect that all flyers, natural and engineered, should belong to the same family given that the laws of flight apply equally to the entire domain [9].

2. Organising the Aircraft Design Space

Since the aircraft design space in general includes all types of flight, including ballistic and buoyant flight, it is necessary for this discussion to narrow it down to the domain of dynamic lift-based flight and to further exclude flight based on propulsive lift and rotorcraft. The domain is further narrowed down to the dynamic pressure of sub-critical flight, but no limits to mass or size are imposed. Important groundwork appears in ref [8] which introduces the notions of the flight objective, the ideal wing, and the inflation factor, as briefly summarised below.

2.1 Flight Objective, Ideal Wing, and Inflation Factor

The design of any practical aircraft inevitably involves compromise to allow for a large variation in objectives and operational parameters. When looking for the ideal arrangement for a design, it is useful to have a reference that is not concerned with the trade-offs leading to such compromise. A reference without compromise must consider a unique objective and set of parameters from the large scope of variations. Here, the notion of the *flight objective* gives such focus. For a focused flight objective, it is in principle possible to derive the ideal aircraft shape within the physical limits of aerodynamics. Here, the notion of the *ideal wing* is introduced as a baseline for any given flight objective. Its size and volume can be uniquely derived from the focused operational parameters. Against this reference, the aircraft volume of a corresponding real solution can be quantified by the *inflation factor*. This factor serves as a measure of the discrepancy between a practical solution and its aerodynamically possible ideal. As a metric for relative aircraft size, different configurations can be compared with the common baseline of their ideal wing.

2.1.1 Flight Objective

Each aircraft is designed for a *family of missions* while every flight represents one *specific mission*. Every mission is composed of a sequence of *mission segments*. Each segment has only one unique *performance objective* such as flying for maximum range or maximum endurance. The family of missions sets the overall scope of *operational parameters* of aircraft mass, air density and flight speed. Each specific mission narrows down the scope of operational parameters while all the performance objectives of the family of missions may remain relevant. Each mission segment further narrows down the variation of operational parameters and now only one specific performance objective remains relevant. This performance objective, together with the operational parameters, defines the *flight objective* of the segment. An aircraft specialised for such a unique flight objective can be without compromise. While such a hypothetical design does not represent a practical solution, it can serve as a useful reference against which practical designs can be compared.

2.1.2 Ideal Wing and Inflation Factor

Assuming that the physics of lift-based flight requires a dynamic interaction between the flight body and its surrounding viscous medium to provide the lifting force for heavier-than-air flight, such a lifting device is assumed to be a wing (a fixed-wing, given the domain under consideration). By 1924, Prandtl and Munk [10-12] had already established how circulation would best be generated to minimise the inevitable loss to induced drag. From the variety of options of stacked and staggered wings of all arrangements, their theory makes a convincing case that the single straight wing with the ideal spanwise circulation distribution would give the best efficiency when no other requirements call for compromise. Best span efficiency is thus a critical quality expected in any solution, ideal in terms of flight efficiency.

Defined as a reference, the *ideal wing* would be the wing causing the lowest total drag physically possible to carry a given weight at the dynamic pressure of choice. With lift being the only consideration, such a wing does not present a practical solution for an aircraft, but it presents the limits of span and volume that are of interest as a baseline for comparison. The ideal wing should be viewed as a hypothetical aircraft with everything compressed into the smallest straight wing of a high aspect ratio to have the lowest total drag possible. This geometry can then serve as a reference against which the quality of deviating solutions can be gauged. Each flight objective has an ideal wing of unique size, depending on the operational parameters and the aerofoil and wing geometry parameters. As fully described in [8], the mathematical relationships have been developed to express the volume of an ideal wing as a function of its operational parameters, namely the aircraft weight, the airspeed and the air density. The ideal wing is taken to have an elliptical planform and is designed to operate at the design lift coefficient and aspect ratio, which together will offer the lowest total drag. The aerofoil geometry is considered by the aerofoil shape and its relative thickness. The volume of an ideal wing is the smallest volume that an aircraft must have to fly a given weight at a selected dynamic pressure at the lowest possible total drag. Comparison with the actual aircraft volume, of a corresponding practical solution of the same all-up mass, yields the *inflation factor*. The inflation factor serves as a quantitative metric for relative aircraft size by which different configurations can be compared against the common baseline of their ideal wings.

2.2 Global Optimum and the Ideal Configuration

Given a focused flight objective, it is in principle conceivable to provide an aircraft design that is specialised for this specific flight objective. This design can be without the compromise otherwise required from flight objectives of other segments of the mission. The best design for a given flight objective is defined as its *global optimum*. By definition, it is physically impossible to meet the given flight objective with any better design than that of the global optimum. It does not matter that such a design may be unknown or not achievable by the current state of technology. By this definition, a unique global optimum must exist for every flight objective.

The design solution of the global optimum must be based on one specific configuration. This is defined as the *ideal configuration* for that specific flight objective. Thus, by definition, each flight objective has only one ideal configuration. Again, regardless of the status of its identity, as a matter of definition, the ideal configuration exists, uniquely linked to its defining flight objective. There may be as many global optima as there are different flight objectives, but the number of different ideal configurations will be relatively small because many variations in the detail will be based on the same basic arrangement and thus belong to the same configuration.

2.3 Principal and Other Mission Segments

Every mission segment has its specific flight objective, global optimum and ideal configuration to which the arguments presented in this work can be applied. The real aircraft must at any time be able to adapt to *all* flight objectives of *all* the segments of *all* the missions required throughout the entire service life. Therefore, it is impossible for real aircraft to operate optimally throughout the full mission. Peripheral mission segments like take-off and climb or descend and landing or any emergency segments, like flight with asymmetric engine failure, must be flyable by the same design at any time. This means that either the same configuration must be suitable to all performance objectives, or it must allow in-flight adaptations (like undercarriage extension) to form derived configurations suitable to other segments. Therefore, general suitability would be a quality one would expect in a candidate family of ideal configurations.

By definition, the principal mission segment has the largest influence on the mission economy and therefore, this discussion looks at the aircraft design space for the group of flight objectives that have the same performance objective as that of the principal mission segments. Flying for maximum range is the most common performance objective. Therefore, this discussion considers, as an example, the design space for the objective of flying with minimum drag at the dynamic pressure of choice.

2.4 Developmental Steps in the Aircraft Design Space

To organize different configurations within the aircraft design space it is helpful to begin with a portion of the set of requirements for which a global optimum can be derived. To recognize the progress in complexity, one may imagine further developmental steps within the set of requirements. Here, the following order of development is imagined:

- Step 1: Provide lift to balance weight at the operational parameters of choice
- Step 2: Maintain the balance of the forces of flight
- Step 3: Control the forces of flight
- Step 4: Provide volume for a payload
- Step 5: Provide propulsion.

2.4.1 Ideal Wing

If the first set of requirements calls only for the provision of lift at the operational parameters of choice, then the ideal wing is the global optimum, and its configuration is the ideal configuration. If the configurational map should show ideal configurations at every developmental level, then the ideal wing can be shown at the first level. As such it can be considered as a common ancestor in an imagined evolution of growing complexity.

2.4.2 Protoflyers

The ideal wing solves only the first requirement of flight by providing lift, and it does this with the best aerodynamic efficiency but not in a steady way. For practical flight, the forces of flight must remain in balance. Therefore, the next developmental step in an imagined evolution from the rigid ideal wing must introduce a means of maintaining balance. The *rigid protoflyer* emerges when both longitudinal and lateral stable balance are achieved. A rigid flyer that can sustain flight without control is here

called a free-flight model. The third step brings some means of flexibility into the airframe to offer control over the forces of flight to yield the *controllable protoflyer*. A radio-controlled aircraft that does not require volume for a payload can serve as an example of a controllable protoflyer.

2.4.3 Inflated Flyers

Practical flight requires volume for payloads which evolves during the fourth developmental step. The shape of an aircraft is most prominently influenced by the strategy by which useful volume is provided. While the protoflyer will already be larger than its ancestral ideal wing, the most significant inflation comes from the requirement for volume for the payload and other bulky items of the flight apparatus. The *inflated flyer* is the aircraft that has evolved the volume required for a given flight objective.

Step 5 is not discussed here as any aircraft in the domain under consideration should be viable in its unpowered mode (full engine failure as in an emergency mission segment or, deliberate omission or deactivation as on a glider) and it must therefore meet all the requirements up to the fourth developmental level. Furthermore, the arrangement of the propulsion system is not considered part of the basic aircraft configuration but rather a further elaboration imposed upon it or integrated into it. This order of development allows consideration of externally added, integrated, retractable or detachable propulsion systems.

2.5 Evolutionary Family Tree of Configurations

When viewing the ideal wing as the common ancestor in an imagined evolution to the inflated flyer, new branches emerge at every developmental step, given the diversity of strategies available to resolve each new challenge. Therefore, the aircraft design space can be arranged along these diverging lines or branches of diverse strategies into different species of inflating flyers, as illustrated in Fig. 1. The inflation factor serves as a measure by which the consequence of progress on aircraft size can be quantified and compared. In the following discussion, five of these lines will be explored on which *actual* implemented inflated flyers are found.

2.5.1 Longitudinal Stability

The ideal wing is specialised for lift at the lowest drag possible, requiring a cambered aerofoil so that the ideal wing is unstable. If a stable aerofoil is used, the best combination of the aspect ratio and design lift coefficient would be at lower values for both. Then, the resulting wing is inflated due to having a larger surface area and, due to the lower ideal aspect ratio. Alternatively, a second wing could be employed, held together by a joining structure. This solution is inflated due to the joining structure and the larger total surface area. If these two approaches are seen as longitudinally stable descendants of the ancestral ideal wing, then two distinct families emerged, the family of *single-wings* and the family of *multi-wings*.

2.5.2 Lateral Stability and Full Control

The next two steps of achieving lateral stability and then full control are first described for three descendants on the side of the multi-wings. The aircraft record shows a few designs based on the tandem wing configuration of which Rutan's Quickie is a well-known example. Furthermore, any form of proposed joined-wing arrangements could be seen as members of the tandem wing family.

More numerous in the current aircraft record are the descendants of the multi-wings on the branch of the canard family of which Rutan's Solitaire glider was a useful experiment. Here, the rear wing is much larger than the front wing and is specialised as the main lifting device. With the main wing now able to reach behind the centre of gravity, vertical wings can be placed at the wingtips for lateral stability and control as is done in Rutan's VariEze.

The most popular branch of the multi-wings is that of the current dominant tube-and-wings arrangement (the Pénaud arrangement). Here, the front wing is specialised as the primary lifting device, while a long mass-balanced boom holds smaller secondary wings rather far behind it for longitudinal and lateral stability and control.

On the side of the single-wing arrangements, there are only a few descendants of the straight single wing in the aircraft record. Known as the flying plank configuration, their fully stable inflated flyers have evolved additional vertical wings for lateral stability and control. Pitch control is achieved by changes in the camber of the aerofoil. Among the few flying planks in the aircraft record, the Fauvel AV22 and the AV36 as well as the Pioneer are prominent examples.

A far more popular strategy for achieving lateral stability on single-wing arrangements is to sweep the wings back. The aircraft records show many implementations based on the swept flying wing

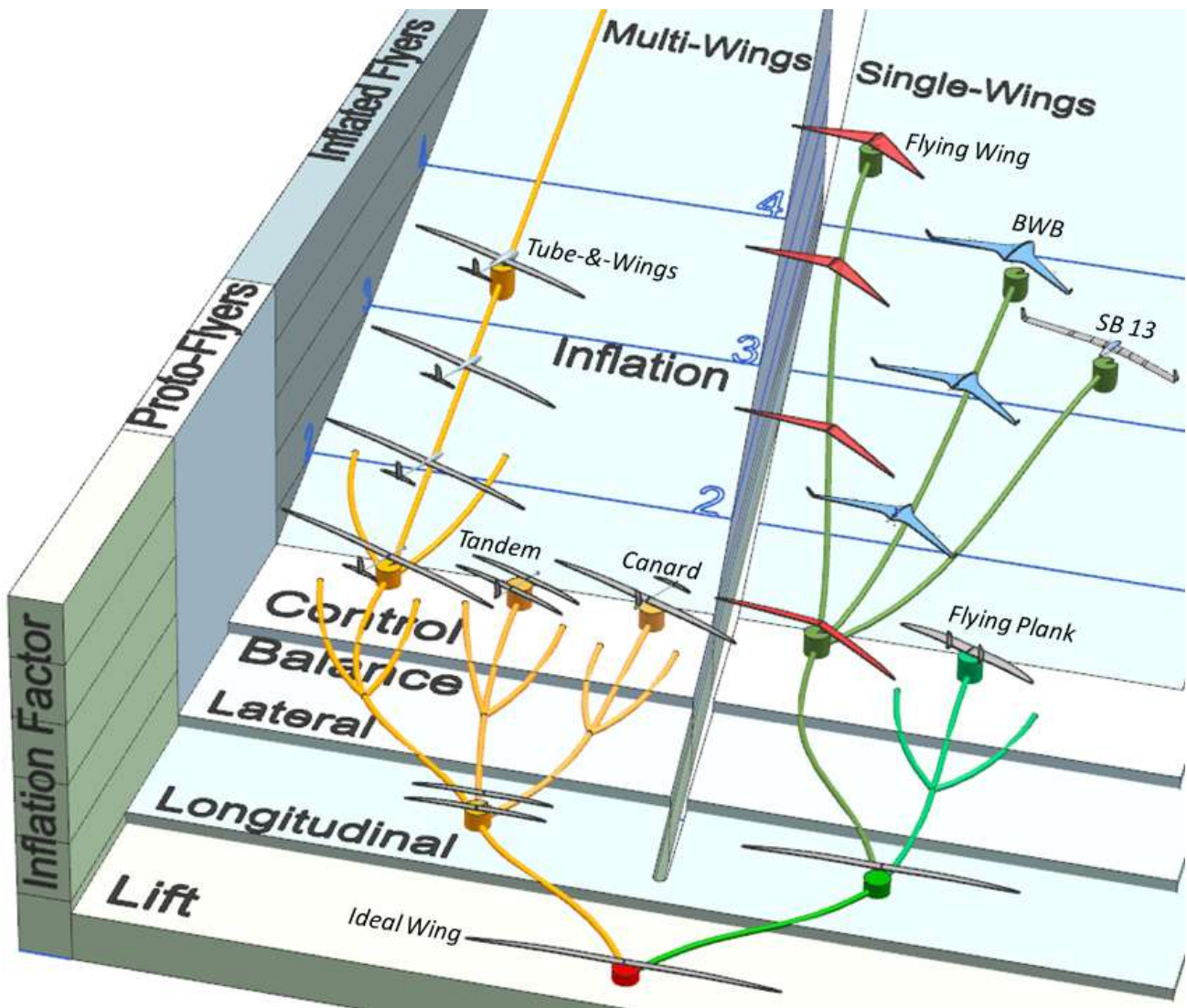


Figure 1 - The imagined evolutionary family tree for fixed-wing subsonic flight with the performance objective of minimum drag. From the common ancestor of the ideal wing the tree branches off into the group of single-wing and multi-wing configurations already at the first developmental step. The inflation factor gives a measure of how an aircraft enlarges as it evolves to meet more requirements. Using the example of a single-seat glider, four tried inflation strategies are shown for the two most prominent protoflyers.

configuration, which can be seen as another fully stable descendant of the ideal wing. The swept-wing form resolves the challenge of longitudinal and lateral stability simultaneously without the need for vertical surfaces. Therefore, the two most prominent competing protoflyers in the current aircraft record are the Pénau arrangement among the multi-wings and the swept flying wing arrangement among the single-wings.

3. Hypothetical Family of Ideal Configurations

From the work of Prandtl and Munk a century ago, it seems reasonable to propose that the global optimum design at the first developmental level, when only lift is required, is the ideal wing. Its configuration, the straight flying wing or the flying plank is then the ideal aircraft configuration for that flight objective. Now the questions are: Which are the ideal configurations for the rigid protoflyer and for the controllable protoflyer and which is the ideal configuration for the inflated flyer? Here, a hypothesis is proposed which implies, that the ideal configurations at every developmental level belong to the same evolutionary line or family, the *family of ideal configurations*.

The hypothesis is formulated as follows:

There exists a single family of aircraft configurations, which holds the ideal configurations for the majority of flight objectives.

This implies that the best strategy for achieving the new function at every developmental level remains the best in all successive developmental levels. Given the large diversity of flight objectives, there

will inevitably be special requirements that have their global optimum and thus their ideal configurations on other branches in the family tree. However, the majority of flight objectives have much in common, so that their optimum designs, when placed into the family tree may show clustering along a common line of configurations.

If this hypothesis has merit, it will have important consequences. For example, in the search for the best aircraft configuration, one could compare strategies at the level of the free-flight model and the radio-controlled model to find the best family among the protoflyers. Given the requirement for general suitability, one could search for the best inflation strategy in fields of aviation with low economic risk before applying it to fields of high economic development risk. The following observations on the current state of air transportation and on the basic principles of design encourage a closer look.

3.1 Currently, a Single Family Dominates

It can be observed in the current aircraft record that a significant majority of *all* flight objectives is being served by a single configuration, which must therefore be recognised as a dominant configuration. It has been dominant since the middle of the previous century. It dominates at every level of development and over the spectrum of size from the free-flight toy to the largest airliner. This observation confirms that it is indeed feasible for a single family to serve a significant majority of all flight objectives in aviation.

However, it must be noted that a dominant configuration is not necessarily the ideal configuration for all or any of the flight objectives to which it is assigned. The fact that it is the selected arrangement does not in itself imply that it is the ideal solution.

3.2 Family Dominance is Expected

The existence of a dominant arrangement is not surprising. For a given performance objective, the variations in the magnitude of the operational parameters may only affect sizes and proportions without requiring jumping between basic arrangements. This is especially likely when the set of different principal performance objectives is small, and in the space of all possible mission segments, there is often a close adherence to operating for either the best range or longest endurance, each of which can be best achieved by the same arrangement of which only the proportions differ. Finally, the laws of physics governing flight are invariant and much commonality even in the details of solutions is thus expected. Commonality at the configuration level would then be far more profound. Therefore, dominance by the same strategies with variations only in the details is expected.

4. Comparing Tried Developmental Strategies

When tracing the variety of lines from the ancestral ideal wing to their inflated flyers, there is an inescapable reduction in flight efficiency due to inflation. The set of new genes which best preserves the ancestral efficiency would express the ideal configuration at any observed developmental level. The hypothesis suggests that all the best strategies will be found in the ideal inflated flyer. *If this is true, then one only needs to identify the best strategy for balance and control and the best strategy for inflation to identify the family of ideal configurations.*

The hypothetical ideal wing offers the best efficiency by providing lift with the ideal span efficiency on a flight body of minimum volume and best span. The developmental strategies have different impacts on the span efficiency and the volume or size of the flight body. Therefore, those strategies which achieve their flight objectives with the best span efficiency and with the smallest inflation factor are likely superior to others. Consequently, one needs to compare the strategies only for their effect on the *span efficiency* and their impact on *inflation* with consideration of the quality of general suitability. This will now be done for the two most popular strategies for balance and control and four well-known strategies of inflation.

4.1 Tried Strategies for Balance and Control

When ideal circulation is induced along the span, the centre of pressure (CP) of this circulation distribution is called the E-point [5]. To be in balance with the ideal circulation, the E-point must coincide with the aircraft centre of gravity (CG). For stable balance, the CP must move to restore the balance in response to disturbance. For control, the CP and the CG must depart to produce controlling moments. The ideal strategy has a stable E-point on the CG and retains the good circulation distribution during acts of control. The strategies for balance and control of the two competing protoflyers will now be compared.

4.1.1 The Pénau Protolyer

The Pénau protolyer adds the mass-balanced tail boom and the secondary wings of the empennage to the ideal wing. The secondary wings are not always productive but in the typical implementation, they are always present adding some mass and drag together with the tail boom, as reflected by some direct inflation. In terms of span efficiency, the boom causes a disturbance of the ideal spanwise circulation. While this may be negligible for the small boom of the protolyer, it is an inherent deficiency of this arrangement. The strength of this strategy comes from isolating the function of the main wing from the function of the stabilisers and the controls. In consequence, span efficiency is insensitive to deviations from the angles of balance caused by disturbances or inputs of control. Therefore, this strategy offers a robust and simple solution to the challenge of stability and control, but it introduces some undesired inflation.

4.1.2 The Swept Wing Protolyer

The swept wing offers pitch and yaw stability without the need for additional features and no inflation is introduced by a boom or any vertical wings. Therefore, it is widely regarded as the purest aircraft arrangement, not deviating much from the ideal wing. This consideration motivated many developments throughout the history of aviation, offering solutions comparable with their Pénau rivals. In their work, the Hortens found that the E-point would not be in the centre of gravity if good handling qualities were given priority [5, 13]. Also, if wing-based controls are employed for change of balance, there is a direct adverse coupling between control and the circulation distribution, which can be detrimental to the span efficiency [5]. Furthermore, most implementations use stable aerofoils, with qualities inferior to those of the ancestral ideal wing. This introduces some inflation of the wing, not as useful volume but to meet the requirement for lift.

Perhaps the best arena for observable comparison of the two rival protolyers is the contest by the radio-controlled gliders of the F3B class. Such aircraft are essentially without a requirement for volume. The flying wing has made prominent attempts to achieve superiority, however, so far, the Pénau arrangement has dominated in these contests [5].

4.2 Tried Strategies for Inflation

One may now imagine the evolution to continue from the protolyer into diverse species of different morphology as new generations show incrementally inflation to provide useful volume. From a larger set of possible inflation strategies, four tried strategies of historic significance are compared in the following sections.

4.2.1 Inflating the Boom of the Pénau Protolyer

In the Pénau protolyer, the boom serves only as a joining structure between the main wing and the secondary wings and to provide mass balance. Given its availability and the need for mass balance, the boom is the obvious element to serve as the payload container as it does in the current dominant configuration. The influences on span efficiency and redundant volume will now be discussed as the boom inflates to meet the demand for volume as illustrated in Fig. 2.

The boom length is dictated by the required location of the secondary wings and the requirement for mass balance. Therefore, inflation comes with the growth of diameter in some portions of the boom. With growing diameter, the boom occupies a growing portion of the wing which adversely modifies the spanwise circulation distribution [14].

For reasons of mass balance, it is often not practical to use the aft part of the boom for the payload. This leads either to redundant volume or at least to a fineness ratio, which is not ideal in terms of viscous drag [15] and mass. The strength of this strategy is that it can offer virtually any inflation factor as demonstrated by extraordinary examples like the Beluga transport plane.

4.2.2 Inflating the Swept Wing Protolyer

The swept wing protolyer can be called a flying wing and many examples of flying wings in the aircraft record can be viewed as inflated swept wings when compared to their imagined ancestral ideal wing. The idea of having nothing else but the wing has been pursued by several designers, perhaps most vigorously by the Horten brothers [13]. To provide useful volume the entire wing has been inflated. Initial small inflation can be accomplished by increasing only the aerofoil thickness while the original wing planform (and thus wing loading) remains unchanged. In this case, the increase of the wetted surface is negligible. Further inflation will require distortion of the planform or scaling by which the wing size increases beyond the minimum of its ancestor. Wing loading lowers to suboptimal values,

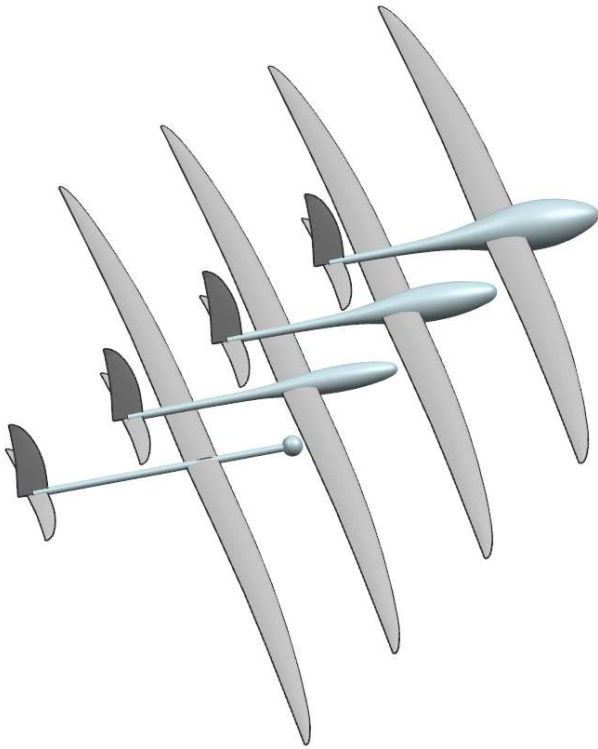


Figure 3 - Boom inflation of the Pénau protoflyer showing a reduction of aspect ratio and growing interference of the fuselage with the wing.

and the lower lift coefficients and aspect ratio no longer comply with the best C_L - AR combination. Now wetted surface grows rapidly with inflation due to the poor volume-to-surface-area ratio of an aerofoil, and the quality of the solution rapidly decreases. Furthermore, not all wing volume is practically useful and thus much redundant volume is introduced before meeting the requirement. Therefore, the flying wing is not suitable for flight objectives requiring large inflation. This may explain why so few pure flying wings have ever been built. The swept wing protoflyer can be called a flying wing and many examples of flying wings in the aircraft record can be viewed as inflated swept wings when compared to their imagined ancestral ideal wing.

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which the wing size increases beyond the minimum of its ancestor. Wing loading lowers to suboptimal values, and the lower lift coefficients and aspect ratio no longer comply with the best C_L - AR combination. Now wetted surface grows rapidly with inflation due to the poor volume-to-surface-area ratio of an aerofoil, and the quality of the solution rapidly decreases. Furthermore, not all wing volume is practically useful and thus much redundant volume is introduced before meeting the requirement. Therefore, the flying wing is not suitable for flight objectives requiring large inflation. This may explain why so few pure flying wings have ever been built. Figure 3 illustrates the inflation of the swept wing protoflyer to remain a flying wing. The requirement for volume is strongly influenced by the relative grain size of the payload or other bulky items. The example illustrates a single occupant defining the volume requirement. To show how ineffective this inflation strategy is, the occupant is placed in the prone posture, as the Hortens did with most of their gliders [13]. This posture needs less wing depth than that required by the more popular supine pilot posture, but even then, the redundant volume

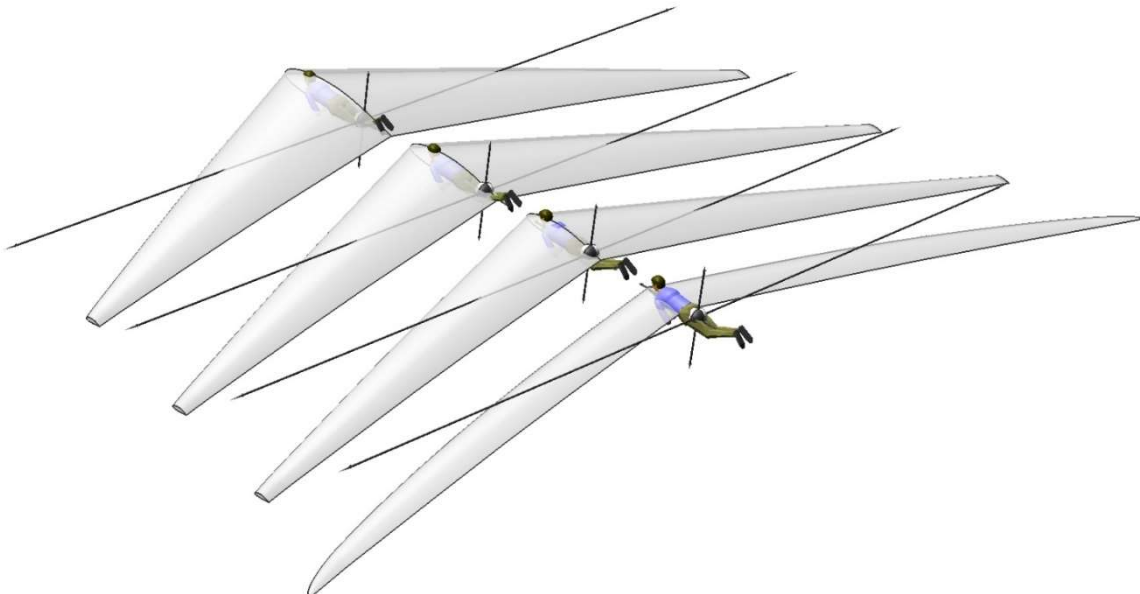


Figure 2 - Wing inflation of the swept wing protoflyer to remain a flying wing until the volume is sufficient to enclose a pilot in the prone posture.

introduced is substantial.

The ideal wing is sized for the design lift and drag coefficients. Any growth of the wing from this ideal reduces the required lift coefficient, and retention of the original chord distribution is then no longer necessary. The ideal spanwise lift distribution can be obtained by aerodynamic tailoring of the aerofoils along the span and the planform shape can be chosen in favour of more volume. It is then more practical to adopt the tapered wing as reflected in many historic examples. With the lower design lift coefficient, it is pointless to retain the high aspect ratio and thus the inflation of the flying wing is characterised by a reduction in span and taper ratio, as shown in Fig. 3. Even this strategy has hardly ever been taken to the full extent. To meet the grain size requirement, an additional deviation from the principal wing shape can normally be found in the aircraft centre. Even so, the resulting wing encloses a large volume, which has seldom been useful for more than the wing structure, the power plants, and the fuel. Flight objectives involving high payload densities and small relative grain size (like bombs) do not need much inflation and then the flying wing can be a suitable arrangement as demonstrated, for example, by the Northrop Y-49.

4.2.3 Inflating the Central Portion of the Swept Wing Protoflyer

To reduce the penalty of redundant volume incurred by inflating the entire wing to retain the flying wing configuration, a different strategy inflates only part of the wing. One such approach yields the blended wing body configuration. The central inflation would typically affect the wing chord and thickness, and the resulting aerofoil may be aerodynamically compromised in favour of the volume requirement. The resulting body is blended with the remains of the ancestral wing, as shown in Fig. 4. An attempt can be made to shape the wing and body by design and to adapt them in flight such that the ideal spanwise lift distribution of the ideal wing is preserved. This requires that the wing should operate with very low local lift coefficients in the region of the body and its blends.

By this definition, many of the Horten aircraft like the H IX and even the H IV are actually blended wing body aircraft though they are typically referred to as flying wings in the literature [13]. Since wing inflation seems to dominate their inflation, as evidenced by their low wing loadings [5], one could accept them as flying wings, albeit not pure. This example demonstrates that species cannot always be classified unambiguously, as the inflation strategies can also be combined in various ways.

The blend may introduce redundant volume when considering the relative grain size of the payload. Therefore, the blended wing body is not particularly suitable for flight objectives with payloads of large relative grain size like the pilot of a sailplane. Hence, it is mostly considered for larger aircraft when grain size becomes compatible with the depth of the wing [16, 17]. Therefore, also this inflation strategy has poor general suitability.

4.2.4 Inflating a Discrete Body on the Swept Wing Protoflyer

If inflation of the central portion of the wing is achieved without retaining the aerofoil shape or edge and surface continuity, then another species emerges. Imagine the development of a dedicated central fuselage, which no longer preserves the form and function of the wing. Initial central inflation

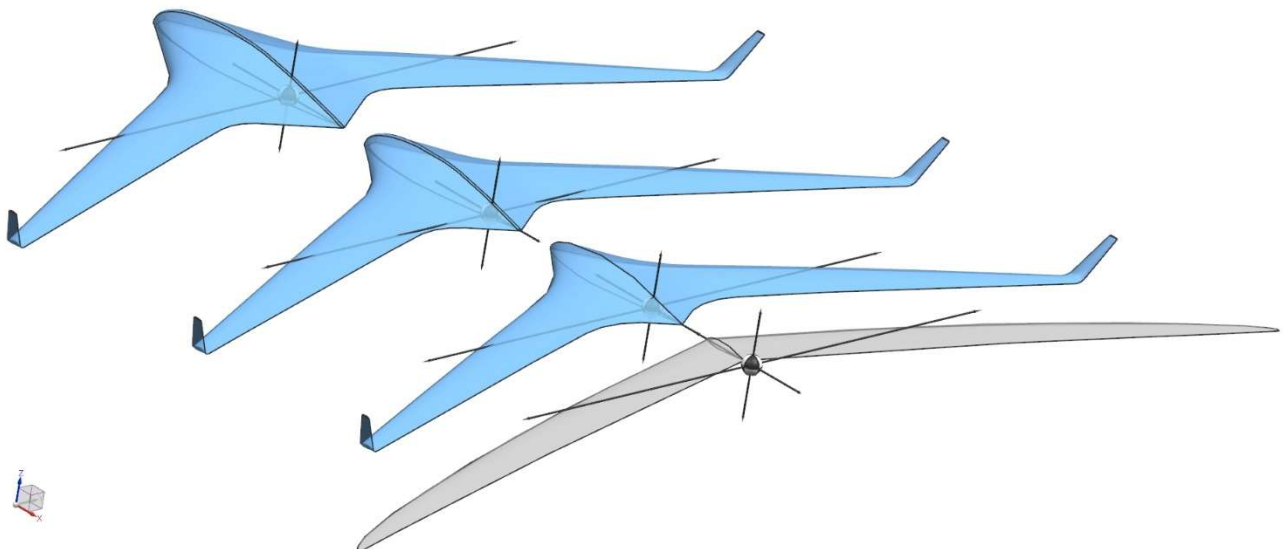


Figure 4 - Wing inflation of only the central portion of the swept wing protoflyer to become a blended wing body.

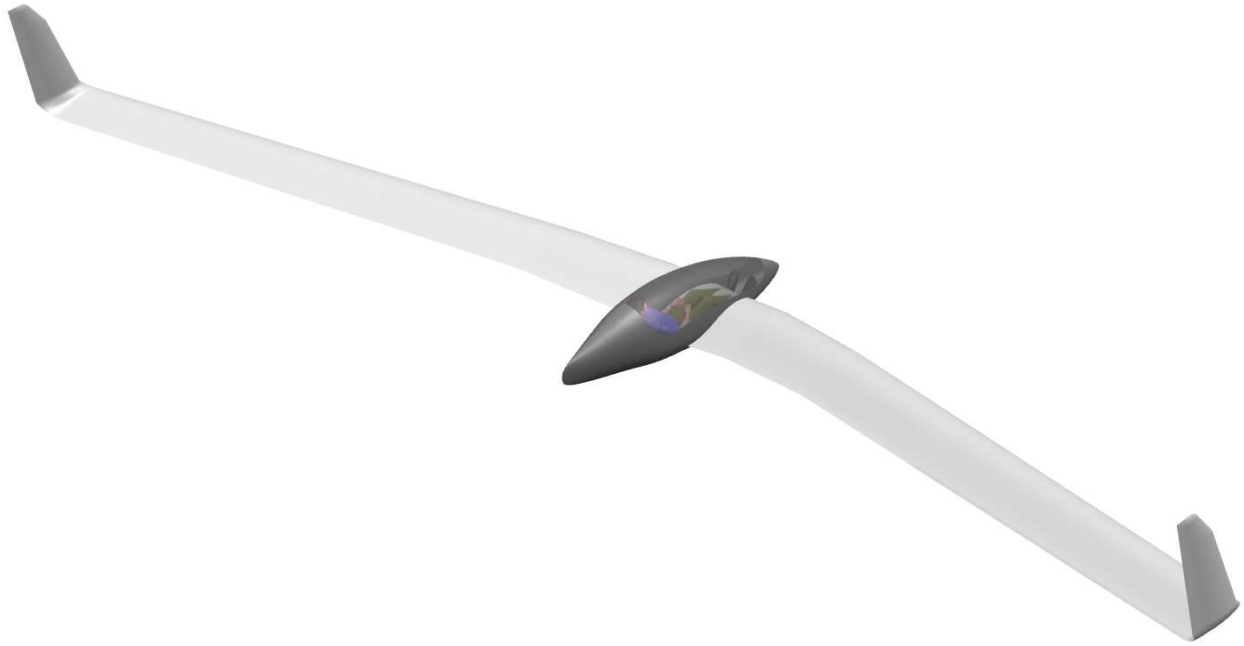


Figure 5 - The SB-13, an example of inflating a discrete body on the swept wing protoflyer.

still yields the body blended with the wing until the continuities of the wing edges and the wing surfaces are broken. This inflation strategy can specialise the container around the payload for minimum mass and drag. For minimised drag, its fineness ratio will offer the best volume-to-wetted-surface ratio which separation-free pressure recovery will allow by terminating the body in a pointed trailing tip.

Torenbeek [2] refers to this as the discrete wing-cum-body arrangement in which also the wing can retain its specialisation as the lifting device. Stinton [18] would classify this under the *classical family* of arrangements having a distinguishable lifting device and a distinguishable non-lifting payload container as in the classical Pénau arrangement. In contrast, the previous two inflation strategies he would classify under the *integrated family*. With the separated specialisation of wing and body, inflation no longer has a direct impact on the wing geometry and the body can in principle be inflated to any scale without the penalty of redundant wing volume. However, the fuselage which thus emerges does not contribute to stability or lift. A body of the shape described is aerodynamically unstable and will not generate useful circulation. Balance must come from the wing, which will then have to grow with a growing body to compensate for the escalating influence of the unstable fuselage. This departure from the ancestral wing then introduces a penalty of redundant volume in the wing. Therefore, this inflation strategy becomes unattractive for large inflation factors.

The SB-13, shown in Fig. 5, a well-known representative of a discrete wing and body arrangement, demonstrates that passive stability at this inflation factor can still come from the wing alone. However, the challenging handling qualities of this aircraft [19-21] suggest that these proportions of wing and body may already be at the limit of acceptability. This may be a reason why further refinement of this specific design approach has proved to be difficult.

5. Considering Alternative Strategies

All the strategies described above have some deficiencies, as briefly summarised here. The inflated flyer of Pénau does not fly with the best span efficiency and is inflated more than would be necessary. The loss in span efficiency comes from the boom inflation and inflation is more than necessary due to the additional components, already at the level of the protoflyer and later due to the emergence of redundant volume in the boom. The strength of this strategy is due to its insensitivity to the inflation factor giving it the best general suitability.

The inflated flying wing has poor span efficiency and is not suitable for large inflations. Span efficiency is poor, already at the level of the protoflyer due to the inferior strategy of balance and control that is typically implemented. Even if a better strategy for control were implemented, inflating a wing is a poor strategy because wing loading reduces, the volume-to-surface area ratio is poor and much redundant volume emerges with inflation. Also the blended wing body necessarily encloses some redundant volume and neither is suited for payloads of large relative grain size. Therefore, neither offers good general suitability.

The discrete body on the tailless aircraft is shy of large inflation as it yields an unstable body. Also here, the typical strategy of control degrades span efficiency, already at the level of the protoflyer.

If one were to accept the Pénaud protoflyer to employ the superior strategies for balance and control, one might want to consider another inflation strategy to arrive at the inflated flyer. Junkers tried an inflated wing [22] and Burnelli tried the central wing inflation [23], both involving an empennage. Both approaches had little impact on the development of aviation.

The boom inflation can be seen as a special form of discrete body inflation. Initially, both have good general suitability, but the discrete body inflation described above has a limit. Boom inflation does not have this limit due to the presence of the empennage. However, the empennage constrains fuselage specialisation as the ideal fineness ratio can typically not be applied. Recognising that the deficiencies of the Pénaud family relate to the boom and empennage, an alternative protoflyer must be found in the family of the single-wings before searching for an alternative inflation strategy based on the concepts of the discrete body inflation.

5.1 Alternative Strategy for Balance and Control

If one accepts the presented hypothesis, that the same family holds the majority of ideal configurations, and, if the explored configurations are not ideal, then the search for an alternative must start afresh at the ideal wing. One must reconsider the options to achieve the development of the rigid protoflyer which is longitudinally and laterally stable. Furthermore, as the considered strategy of control of the single-wing seemed problematic, another strategy for control must be considered for the controlled protoflyer.

Consider the flying plank as the first single-wing descendent of the ideal wing, in which the camber is articulated, either passively as for the rigid protoflyer, or actively to allow control. Then the swept wing could be a descendant of the flying plank, in which the trait of central planform articulation emerged. As such, the swept wing is simply a different posture of the ideal wing. Perhaps other postures could be adopted if more articulations of the planform and dihedral were allowed. Consider the flying plank which has three articulations approximately equally spaced along the span. It can hold a longitudinally stable posture as a flying plank by having a stable aerofoil on a straight wing, but it can also hold the posture of the swept wing, which requires less reflex for its aerofoil. In the swept wing posture, the structural centre has departed from the centre of gravity of the wing, thereby introducing longer load paths into the structure of any practical flyers. With the additional articulations along the semi-span, a planform can be obtained in which the structural centre remains in the centre of gravity of the wing, while the longitudinal location of the wingtips and special polyhedral angles can be set in favour of lateral stability. Because such wing postures can be observed in nature, this arrangement is here called the gull-wing form (Fig. 6).

Any shape expressed in subsequent generations may then merely be a variant of the posture in the same family of configurations. If these articulations become active features, inflight morphing of the posture could serve as a more elaborate strategy of control.

It is here proposed that the gull-wing form should be recognised as a *special posture of the ideal wing*, which emerged after evolving appropriate articulations of camber, planform and dihedral. Ref [9] demonstrated one *specific posture of this form that offers acceptable stability, both longitudinal and lateral. It was also demonstrated that in-flight changes of the posture can serve as a useful elaboration of the strategy of control.* This approach certainly appears to be a promising alternative to the ideal

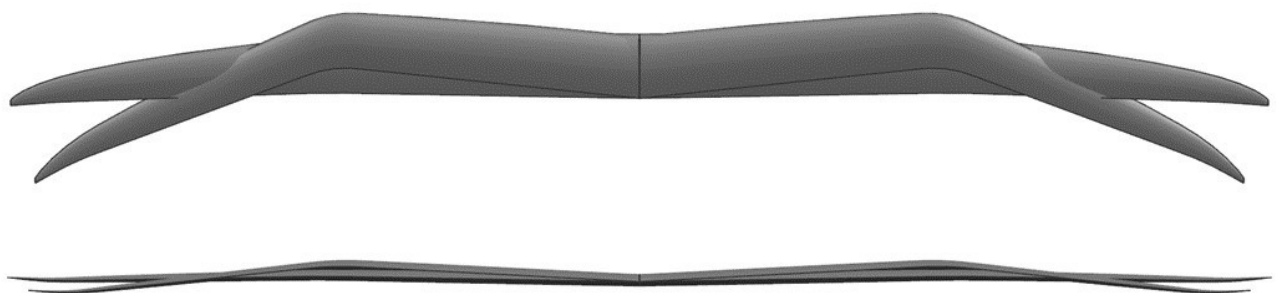


Figure 6 - The ideal wing assumes a different posture to form a fully stable protoflyer in which the structural centre and the centre of pressure remain coincident. This is achieved here by a central articulation, and articulations at the wing wrist and the wing tip to change sweep and dihedral angles. Other articulations are conceivable while remaining on the same branch of the configuration map. These can be viewed as variables of design but may also be variables under active control [9].

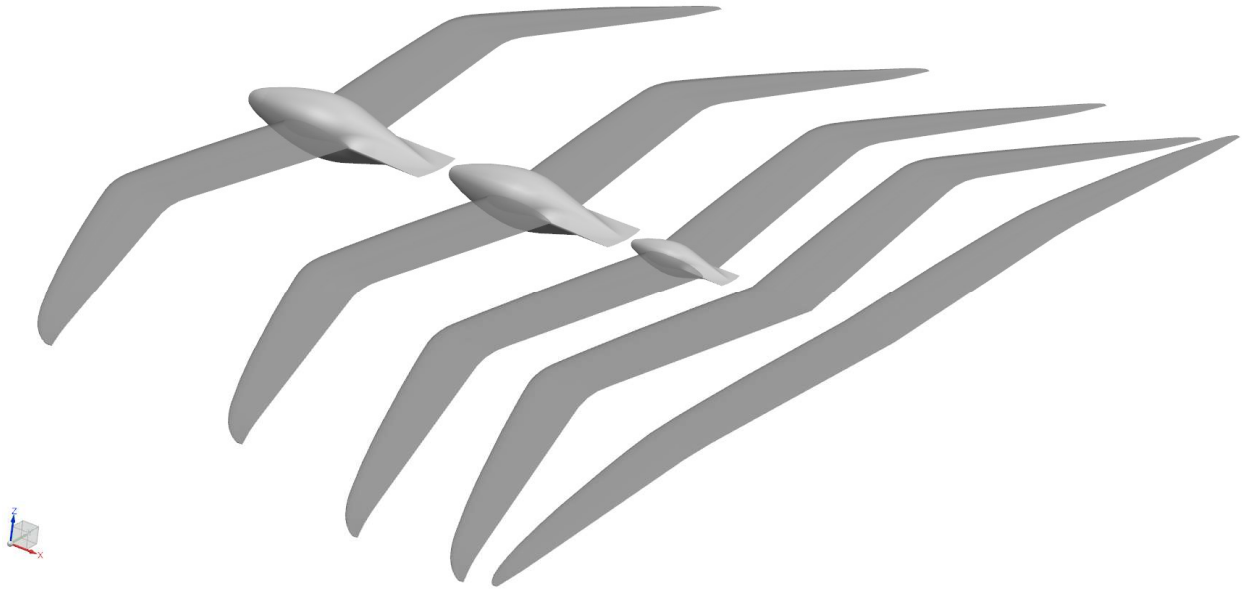


Figure 7 - The ideal wing assumes a stable posture and then begins to grow a stable body to any required inflation factor.

wing fitted with a boom and empennage.

The remaining question is: Which inflation strategy can best maintain ideal circulation while minimising the growth of redundant volume to allow inflation to any size? This strategy can take advantage of being liberated from the constraints of the boom and empennage.

5.2 Alternative Strategy for Inflation

The discrete body inflation strategy, of which the boom inflation is a special case, appears superior in terms of general suitability but it disturbs the span efficiency. The ideal strategy would allow independent body specialisation to any size without compromising span efficiency. Therefore, it may be helpful to return to the origin of this genetic line where the discrete body emerged, to look for an alternative.

Consider again the emergence of a discrete fuselage, now on the proposed gull-wing protoflyer as shown in Fig. 7. Instead of emerging with a pointed trailing tip, the fuselage retains the wing trailing edge as it grows beyond it. Such a low-drag body with a horizontal trailing edge, as shown in Fig. 8, holds the rear stagnation line to enforce the Kutta condition on the flow around itself. Ref [14] demonstrated that a body with such a Kutta edge placed on a wing induces a circulation about itself to provide downwash whereas a fuselage without it leaves a downwash deficiency instead. Thus, it can serve as a lifting body by which the ideal span efficiency can be retained at any body size. Another important consequence of the fuselage Kutta edge is, that it brings a neutral point onto the body and, with the centre of gravity suitably placed, pitch stability can be achieved on a fuselage of any size. Such a fuselage can be specialised around any payload in favour of mass and drag. As it is stable



Figure 8 - A body specialised in favour of mass and drag with a trailing edge, which serves to induce circulation over the body and to bring a neutral point onto the body. Such a stable lifting body can be inflated to any size while retaining its flight mechanic properties.

on its own at any inflation factor, pitch stability is not demanded from the wing alone. The wing can then retain its ancestral qualities, still providing lateral stability and perhaps pitch stability of its own if necessary.

Such a configuration is insensitive to the inflation factor, like the Pénau configuration, so it will have the same general suitability. In principle, it might allow flight with the ideal downwash distribution in any flight condition. Inflation is not as high as that of its Pénau counterpart because there is no empennage. The fuselage simply scales to the required volume as illustrated in Figs. 7 & 8. Strangely, there are no well-known examples of implementation of such a configuration in the aircraft record.

5.3 The Natural Dominant Configuration

As natural examples of rigid protoflyers, one finds seeds, and among them some fixed-wing gliders. Likely specialised for the performance objective of maximum endurance, the *Zanonia* seed in Fig. 9 is an example of a fully stable rigid protoflyer of low wing loading, which requires insignificant inflation for its payload. Its wing shape has been tried in aviation at times when many aspects of the emerging art of aeronautics were still immature and wing loadings were typically low [5, 13, 24]. Its failure to endure in the gene pool of aviation may have reasons other than conceptual inferiority. Interestingly, a similar wing morphology is recognisable in other unrelated flyers in nature, in the wings of bats, pterosaurs and birds. These can be considered as inflated flyers in the same family. Birds of higher wing loading, like many of the sea birds, show the highest inflation and therefore, this line is described as that of the gull-wing configuration.

The posture of the natural wing is characterised by having its structural centre close to the centre of gravity of the flyer while the wing tips are often behind it. Polyhedral, with anhedral on the outer portions of the wing, is frequently used, perhaps to provide suitable lateral flight mechanic properties. Fig. 9 shows the Kutta edge as a common configurational feature, found in genetically unrelated natural flyers of any inflation.

Figure 10 shows the proposed gull-wing protoflyer and the proposed inflation strategy in the family tree. The best solution achieves its flight objective with the best span efficiency and smallest inflation. The figure shows single-seat gliders designed for the same flight objective. All have been inflated until sufficient for a single pilot so that their relative level of inflation can be compared as illustrated. The gull-wing configuration shows the lowest inflation in the five cases illustrated. The largest member of the gull-wing configuration (top right in Fig. 10) is included to demonstrate the general suitability of this strategy, which can accommodate inflations as large as that of the Beluga of the tube-and-wings configuration. The penguin, an underwater flyer, is an example of a natural flyer of such high inflation. A fuselage that can provide appropriate circulation, can offer span efficiency better than that of the Pénaud configuration.

Does this line perhaps represent the family of ideal configurations? All things considered, it has been the dominant family in nature already for millions of years and if the hypothesis is true, then there should be only one dominant configuration in this domain, not two as is currently the case.



*Figure 9 - The gull-wing morphology can be recognised in most natural gliders even if these are genetically unrelated. The *Zanonia* seed represents a natural example of a free-flight model given that it is rigid and essentially without payload volume. The bat (photo by Romain Pontida, modified) and the pterosaur (by Nomu Tabura) show the discrete body of small inflation, while the sea bird (albatross by JJ Harrison, modified) shows the same at a larger inflation. All feature the Kutta edge on the single central body on a single wing with a posture that may be adapted for favourable flight mechanic properties. All would be placed in the same family in the configuration map, the line of the natural dominant configuration (NDC).*

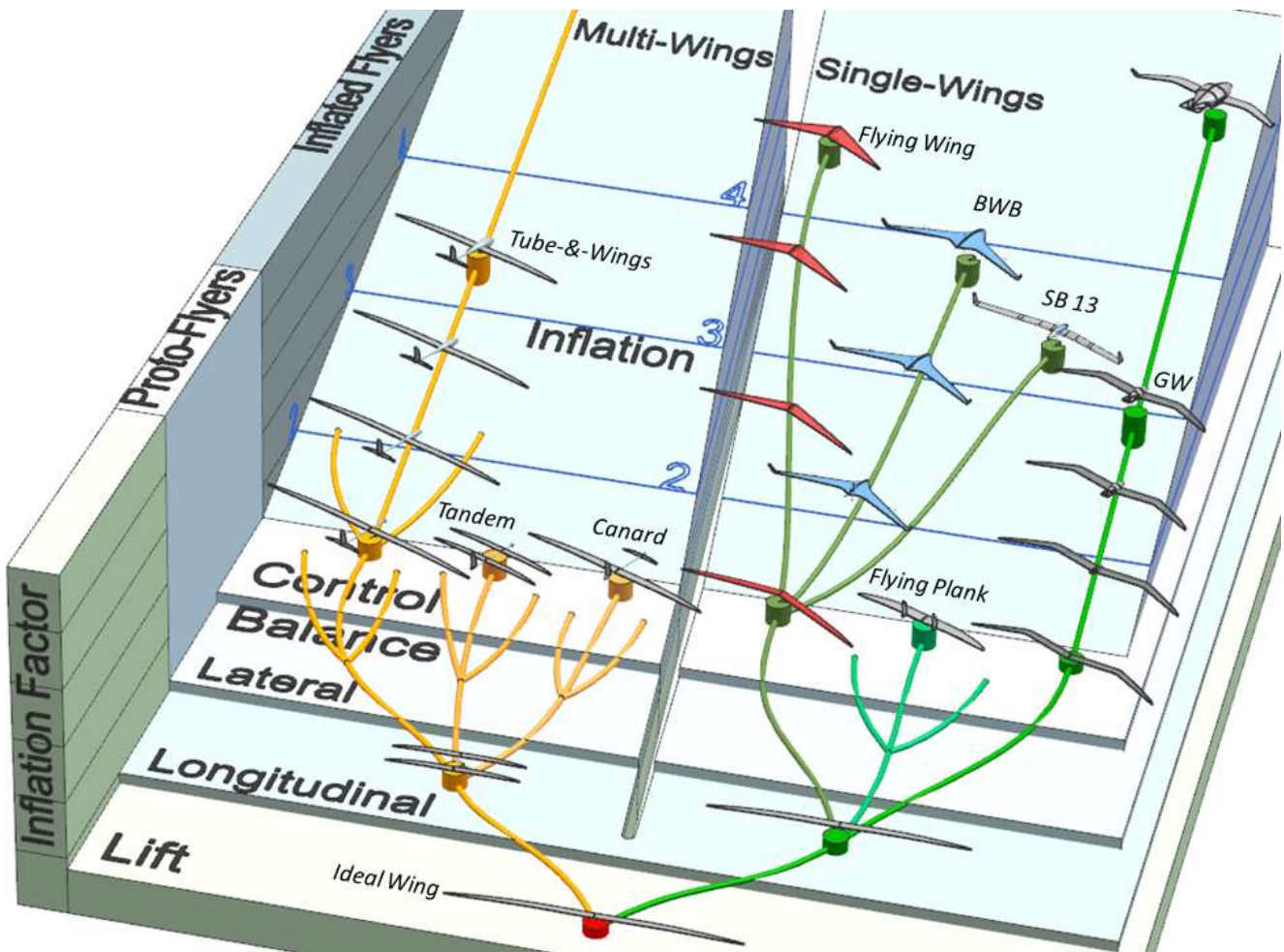


Figure 10 - The family of the gull-wing (GW) configuration is shown on the right, the same line as that of the NDC. Its protoflyer is just another posture of the ideal wing. Of all the inflated flyers, the GW glider has the lowest inflation factor, not only among the single-wings but also lower than the tube-and-wings glider on the left. The five examples shown are sailplanes sufficiently inflated to accommodate a single pilot. Additionally, a much larger inflation on the gull-wing (top right) is included to demonstrate insensitivity to inflation, illustrating general suitability.

6. Conclusion

The aircraft design space was organised into an imagined evolutionary family tree of configurations to consider the oldest question in aviation: *What should an aircraft look like?* The notion was proposed that the ideal aircraft configurations for the majority of all flight objectives belong to the same family, the family of ideal configurations. While it cannot be demonstrated that this notion is true, it has been demonstrated that it *can* be true and that it is rather likely to be so. Qualitative comparisons of existing configurations in the aircraft record suggested, that none considered were candidates of the proposed family of ideal configurations. Inspection of alternative developmental strategies revealed the branch on which most natural flyers would be mapped in the family tree. This seems to be a viable candidate for the proposed ideal family.

7. Recommendation

If a single aircraft family is indeed ideal for the majority of flight objectives and if the current dominant configuration is not the family of ideal configurations, then the priorities and structures concerning aircraft development ought to change accordingly. A better candidate must be found as a matter of urgency, and gradual implementation and refinement ought to commence as soon as possible. One could begin by exploring at the level of the protoflyer and one could search independently for the best strategy of inflation. One may apply any proposed strategy to any flight objective in the given domain and it is then sensible to choose a field of low economic development risk to give the new technology a chance to become established, refined, matured and accepted before applying it to flight objectives of high economic development risk. The protoflyers could battle out supremacy in competitions among free-flight models and in the arena of the radio-controlled gliders, perhaps in the class of

F3B [5]. For the inflated flyers, the scene of gliding has often served as an incubator for new technologies in aviation [25]. The current best sailplane has the same configuration as the current best airliner. If a superior configuration exists for the sailplane, it would most likely be superior also for the airliner. Therefore, the scene of gliding could serve to test the ideas proposed here.

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