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STRUCTURAL DESIGN CONDITIONS FOR HUMAN POWERED AIRCRAFT

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Abstract

The operational needs of human powered aircraft (HPAs) are significantly different than those of most aircraft. Consequently, the standard V-n diagram is not directly applicable to HPA structural design.. A different set of structural design conditions, based on their operational needs, is proposed for HPAs. These design conditions concern steady loads, maneuvering loads, and gust loads. Steady loads determine some of the stiffness requirements of the structure, and require the selection of a maximum operating speed (Vmax). Maneuvering loads are dependent on the maneuvering speed (Vm) and maximum sideslip angle (βmax) selected. The design load factor, Ndes, is derived from Vm and the stall speed. Gust loads are more of an operational problem than a structural one since they become a control problem before they substantially affect the structure. The assumption of a rigid structure in calculating loads is not applicable to HPAs. Structural deformations must be taken into account.

Introduction

Human powered aircraft (HPA) have limited power available from their human engine. Hence, low power is the critical measure of performance. Because the power needed to sustain flight varies as $(\text{weight})^{3/2}$, low weight is extremely important to HPAs, and is a major goal in HPA design.

One of the largest weight components of an HPA is its primary structure. To properly design the structure one must determine:

1) the appropriate design flight conditions, and

2) the structural loads caused by these flight conditions.

Neither of these is immediately apparent. The flight regime and maneuvering requirements of HPAs place very different demands on their structure as compared to more conventional aircraft. Also, due to the size and flexibility of HPA structures, secondary loads normally neglected in conventional aircraft become critical for an HPA.

This paper addresses the determination of appropriate structural design conditions for HPAs. The *Daedalus* HPA is used as an example to illustrate some of these structural design conditions.

Structural Design Conditions

The structural design conditions for conventional subsonic aircraft are usually specified in the form of a V-n diagram. Such a diagram defines the structural design conditions in terms of limit load, ultimate load, maneuvering speed, never exceed speed, and maximum normal gust velocity. Limit load is usually specified by regulations, depending on the aircraft category, with ultimate load being defined as limit load times a safety factor, usually 1.5. The maximum speed at which any control input will not allow limit load to be exceeded (usually because the aircraft stalls) is defined as the maneuvering speed, its actual value depending on the aircraft's stall speed and limit load factor. Never exceed speed is usually limited by flutter considerations, while the maximum normal gust velocity is defined by regulation.

Unfortunately, the V-n diagram approach to structural design conditions definition is not directly applicable to HPAs. The general concept of limit and ultimate loads, separated by a constant safety factor, is inefficient. In general, HPA structures have sudden and catastrophic failure modes, either through buckling (both global and local), brittle failure (as is typical of composite structures), or loss of the primary, and only, load path. It is thus more efficient to stress the aircraft to a design load and apply a different, and usually lower, safety factor during the detail design depending on the failure mechanism. Maneuvering speed is still useful in the design of HPAs if we change its nature, and use it to define the design load. The never exceed speed speed takes a different character, more closely linked with divergence and unacceptable deformations, rather than flutter. Finally, maximum gust velocity becomes a non-issue as will be shown.

We will define an alternate to the V-n diagram approach to design load cases. The structural design cases will be divided into steady loads, maneuvering loads, and gust loads.

Steady Loads

By steady loads we mean those that act on the aircraft in unaccelerated flight at design speed(s), or while the aircraft is stationary. Although these are the easiest design cases to define, it is extremely important that they be met properly, specially in terms of structural stiffness, since it will severely affect the performance, controllability, speed range, and operational ease of the aircraft.

1g Flight At Design Speed(s)

This condition will have the most relevance in defining the bending (EI) and torsional (GJ) stiffness of the wing.

Since most HPAs have relatively flexible structures, their dihedral is strongly affected by the bending stiffness of the wing structure. Most HPAs depend heavily on the yaw-roll coupling provided by the dihedral for both their stability and control. Thus, it is important to select a bending stiffness distribution which will produce the desired dihedral. Figure 1 shows a front view of the *Daedalus* HPA in 1g flight at the design cruise speed of 6.7 m/s.

The desired dihedral, defined by a tip deflection of 2.0 m, was obtained by proper matching of the wing spar's EI distribution, and the lift wire's length and stiffness. Note that in an HPA such as *Daedalus*, the wing dihedral can still be varied at a later date by installing a lift wire of different length or stiffness. If the wing structure was fully cantilevered, the dihedral would be set, and difficult to change without major modifications.

Just as important is the GJ distribution of the wing structure. In order to approach the optimum elliptical lift distribution, the wing twist distribution due to aerodynamic loads must be known in advance, so that it can be taken into account during fabrication. The wing structure's torsional stiffness also has a strong bearing on the maximum operating speed.

Maximum Operating Speed, Vmax

For HPAs we propose defining a maximum operating speed, Vmax, at or below which the aircraft should be free of unacceptable deformations, aeroelastic divergence, and flutter. This speed is closely related, but not identical, to Vne in conventional aircraft.

Figure 2 shows the wing deformation and lift distribution for the *Daedalus* HPA at two speeds: design cruise (6.7 m/s), and Vmax (11.3 m/s). As speed increases, the wing pitching moment twists the wing, unloading the tips, and reducing the bending moment. Since the dihedral is generated by the bending of the wing structure, dihedral is lost as flight speed increases. The *Daedalus* HPA does not have ailerons, all roll control is effected through roll-yaw coupling. By eliminating all dihedral, the aircraft is left with practically no roll control. Thus, given a maximum operating speed, Vmax, the wing structure's torsional stiffness can be defined. At the same time, the torsion moments will be greatest at Vmax, so the wing's structure torsional strength requirements will usually be defined by this speed.

The divergence speed of the *Daedalus* HPA has been calculated to be well above Vmax. A simple flutter analysis yielded flutter speeds much greater than Vmax, as expected from the aircraft's large size, low mass, and slow speed (even at Vmax). However, which of the three considerations: unacceptable deformation, aeroelastic divergence, or flutter, will become the critical design condition at Vmax, depends on the particular aircraft's aerodynamic and structural configuration.

It should be noted that the proper selection of Vmax is crucial to the aircraft's optimization for its designed task. An HPA such as the *Gossamer Albatross* had a narrow speed range, due to performance and control considerations. Thus, Vmax should be only slightly higher than its design speed. In the case of the *Daedalus* HPA, it is impossible to power the aircraft to Vmax in level flight. However, since *Daedalus* is flown to altitudes in excess of 30 m, speed could easily build up in a dive, so higher Vmax must be chosen.

Attention should also be paid to the fact that Vmax should be greater than the maneuvering speed, Vm, and gentle control inputs should be used at speeds between Vm and Vmax.

Stationary Loads

In some HPAs, loads may exist while the aircraft is not in flight which may be a design critical condition in terms of strength or stiffness. Such design cases will be very specific to each HPA, and the way in which it is to be operated.

For example, in regular flight operations the *Daedalus* HPA is flown with a mast and download wires, to support the wings when the aircraft is stationary or being transported. This mast prevents wing structural damage during ground handling. However, the mast is removed for record flights, since it is not needed once the aircraft is airborne, to further reduce drag and weight. Since it is possible that the aircraft will come to a stop before the wing runners reach the aircraft, it is necessary for the wing to be able to support its own weight. In the *Daedalus* HPA this case defines the wing spar's bending strength for two meters from the aircraft's centerline.

Maneuvering Loads

For HPAs we will define maneuvering loads as those caused by control inputs from the pilot, such as a straight pull-up, from positions in which the aircraft may find itself in during expected flight maneuvers, such as high angles of sideslip, or a combination of these. In general the highest structural loads encountered by an HPA will be maneuvering loads.

Since the loads generated are a strong function of airspeed, one must first define a maneuvering speed in order to accurately assess and calculate these loads.

Maneuvering Speed, Vm

We define maneuvering speed, Vm, as the highest airspeed at or below which simultaneous full control deflections can be made without structural failure occurring.

Extreme care should be taken in selecting the maneuvering speed; the highest loads for much of the structure will be encountered at this speed. Hence, a realistic assessment of the appropriate Vm, given the operational goals of the aircraft, will save weight by making the structure just as strong as it is needed. Notice that by defining the maneuvering speed first, and knowing the aircraft's stall speed, Vs, the design load factor can then be calculated from:

$$Ndes = (Vm/Vs)^2$$

Determining the design load factor in this way is more efficient, since it is closely tied to the operational needs of the aircraft. For *Daedalus*, the maneuvering speed was chosen to be 7.8 m/s. Given a stall speed of 5.9 m/s, the design load factor for *Daedalus* was 1.75 g's.

Not all the worst loading conditions will occur at Vm. As will be shown later, loads due to sideslip will often be higher at slower speeds. Hence, attention should be paid to the speed, not necessarily Vm, at which a given design case generates the most severe loads.

Maximum g pull-up, Ndes

This is the simplest maneuvering case to analyze since it involves only the pitch axis, and all loads and deformations are symmetrical about the centerline. In general, this design condition will generate high bending moments, and thus determine the required bending strength for a significant portion of the wing structure.

If Ndes has been defined by a predetermined maneuvering speed as outlined previously, then it can only be reached at speeds equal to or greater than Vm. If we assume that this maximum g pull-up to Ndes is achieved at Vm, the airfoil will be operating at its maximum lift coefficient and angle of attack. Thus, this condition will also determine the maximum in-plane loads in forward bending on the wing structure.

Maximum Sideslip Angle, βmax

HPAs often encounter angles of sideslip much greater than conventional aircraft. This is due to control and maneuverability problems inherent to HPAs.

In the *Daedalus* HPA sideslip angles of up to 30 degrees were measured. Such large angles of sideslip, coupled with a large dihedral, will generate significant loads on the upwind wing even though the load factor may still be equal to one. The additional wing deflection during this condition increases the loads even further. This stresses the need for analysis techniques that take full account of the structure's flexibility. Notice that this condition does not necessarily become worse as the airspeed increases. Higher speeds tend to reduce the dihedral, and thus the load due to β. Figure 3 shows the wing structural deformation and load distribution of the *Daedalus* HPA at a sideslip angle of 30 degrees.

Together with Ndes, the βmax design condition will usually define the wing structure bending strength requirements.

Turning Flight

Most HPAs are limited to very shallow turns, angles of bank of less than 10 degrees, due to control and maneuverability considerations. Hence, the load factors generated in such maneuvers are very low. Loads in turning flight will usually be covered by the Ndes and βmax design conditions.

However, HPAs keep advancing to higher speeds and more maneuverability. In a future HPA generation, loads in turning flight might become important enough to warrant consideration as a separate design case.

Combined Cases

The design cases just described need not occur in isolation. Thus, an assessment must be made as to what combination of cases is feasible, and to what degree.

For the *Daedalus* HPA it was assumed that a 1.25g pull-up, combined with a 30 degree angle of sideslip was as likely to occur as any of the other design conditions. This situation may arise as the pilot tries to level the aircraft from a steep turn while pulling up to avoid an unscheduled landing. Again notice that this condition is not necessarily at its worse at or above Vm, but that it becomes more severe at a slower speed where the dihedral is greater.

A different assessment of what combination of cases is appropriate must be made for each HPA given its operational goals.

Gust Loads

Assessing the effects of gust loads on an HPA is difficult since little quantitative data is available and applicable. A few comments on how to cope with gusts is the limit of our knowledge.

In general, gust loads will be of little concern to the structural design of an HPA. Due to the low flight speed and limited control authority of HPAs, gusts will be a control and maneuverability consideration before it becomes a structural problem. If flight speed is kept below the maneuvering speed, vertical gusts will present no structural problems, since the aircraft will stall before structural damage is done. However, horizontal gusts may cause flight speed to exceed Vm, causing structural failure.

One possible case where gust loads may become important to the structural integrity of the aircraft, while flying at speeds below Vm, occurs in any HPA wing structure with external bracing. A gust of small spatial length can cause significant vertical velocity variations across the span. The resulting lopsided load distribution can cause excessive bending moments where they would not otherwise occur.

Our recommendation is that gusts be dealt with as an operational rather than a structural issue. Flight in winds which are a significant percentage of flight speed must be undertaken carefully. The crew must be aware of the causes of turbulence, such as upwind obstructions and thermal sources, and learn to avoid them.

Load Determination

Once the appropriate structural design cases have been determined, it is of equal importance that the loads be accurately calculated. In many subsonic aircraft, the loads can be determined to the required accuracy while assuming a perfectly rigid structure. This is not the case for most HPAs. The deformation under load of most HPA structures is not negligible, and these deformations can have a significant effect on the load distribution.

The structural flexibility of *Daedalus* has an important effect on its load distribution in three cases. First, at higher speeds the wing's lift distribution is modified due to the increased twist deformation. This change in the lift distribution causes the dihedral to be reduced at higher speeds, affecting the control and stability of the aircraft. Second, additional wing bending deformations during sideslip incursions further increase the loads on the upwind wing. Third, any in-plane deformation of the wing generates additional torsion moments on the wing structure due to wing sweep. Such in-plane deformations also have an important effect on the aeroelastic divergence of the wing. Maintaining the in-plane deformation of the wing to an acceptable level defines the in-plane stiffness requirement of the *Daedalus* wing structure.

Conclusion

Structural design conditions for HPAs are different than those defined by a V-n diagram. This is due to HPA's narrow speed range, their capability to enter large angles of sideslip, the flexibility of their structure, and the need for calm conditions. The need for extreme light weight also forces a more aggressive structural design with smaller safety factors. By selecting the speeds and parameter in which the HPA is expected to operate: Vmax, Vm, βmax, and applicable combined cases, one should be able to design a structure which has just enough strength and stiffness for the intended purpose, and no more.

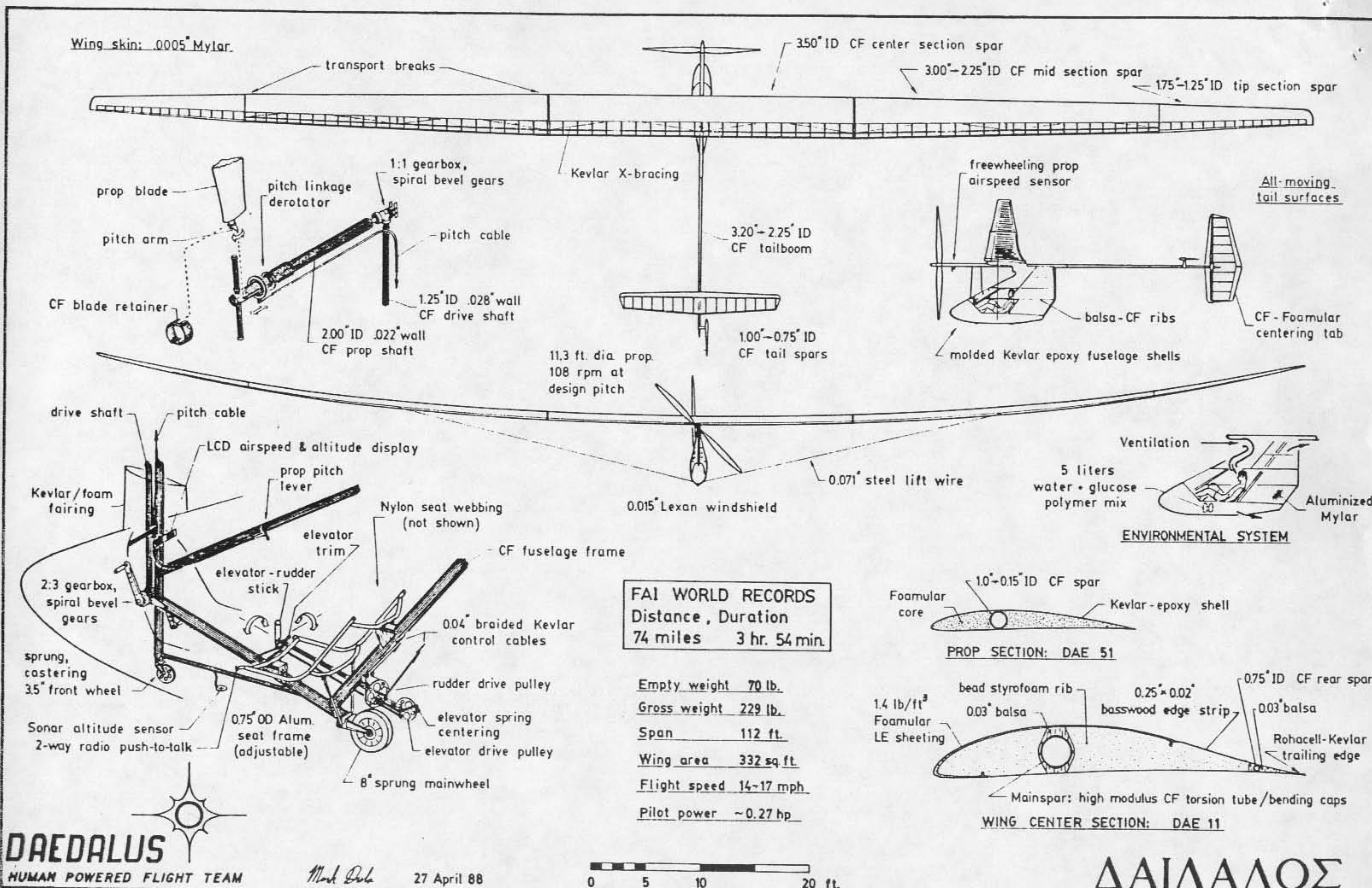

FIGURE 1

DAEDALUS HUMAN POWERED AIRCRAFT

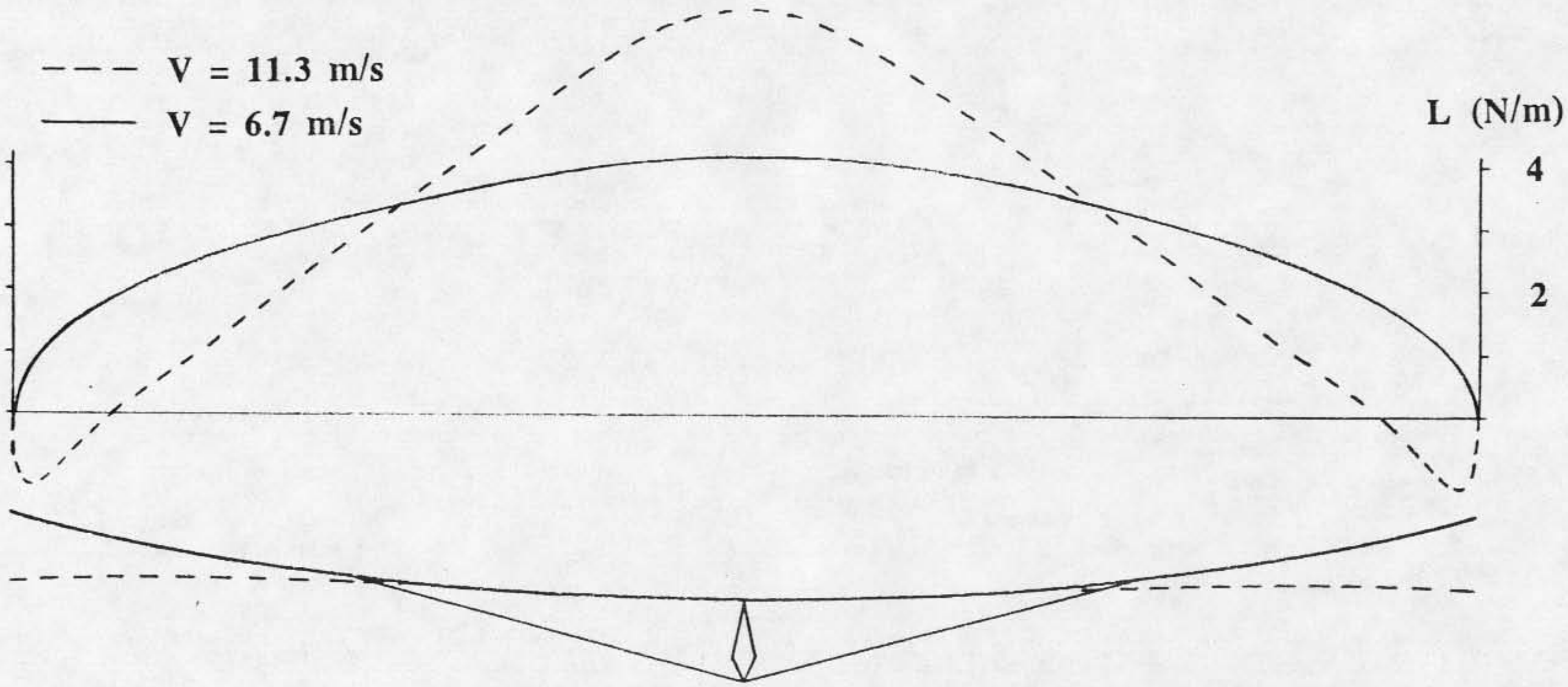

Figure 2
Daedalus Load and Deformation Distributions at Design Cruise Speed and Vmax

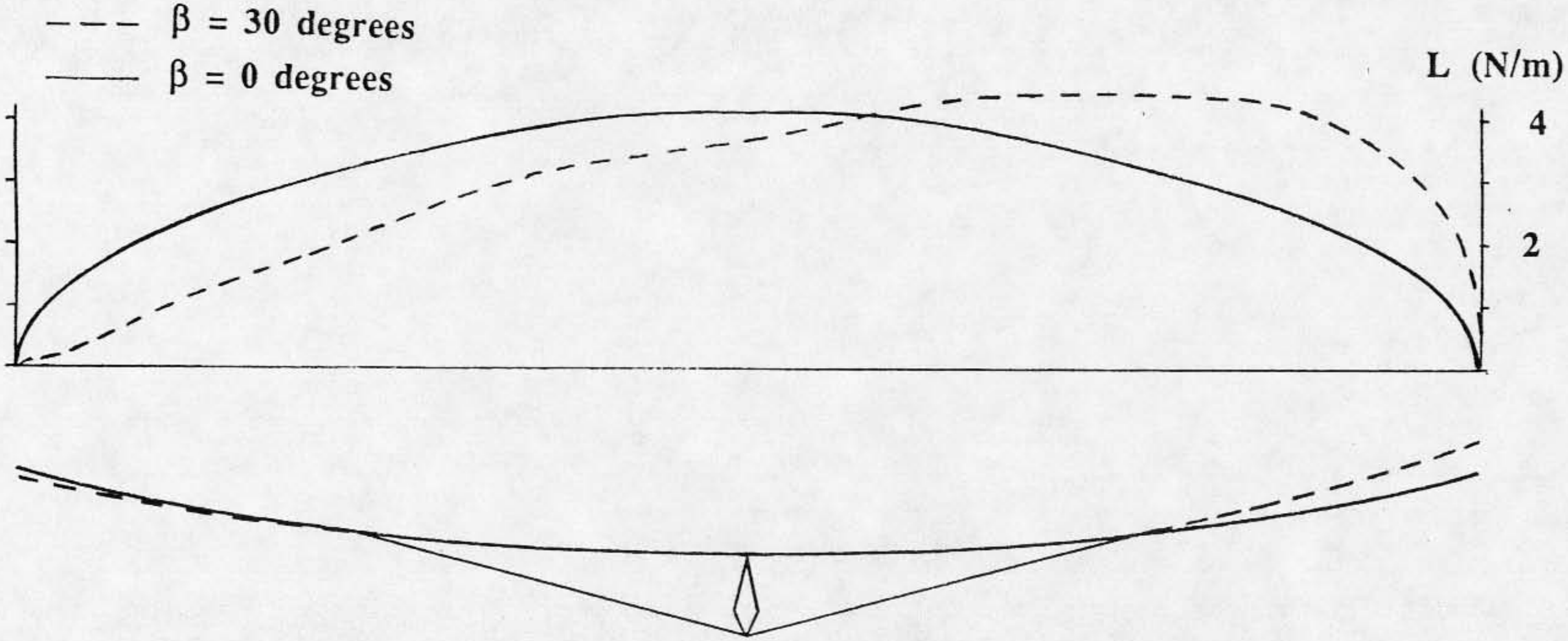

Figure 3
Daedalus Load and Deformation Distributions
at $\beta = 0$ and $\beta = 30$ degrees