New Procedures in Flight Mechanics to Analyze the

Stability and Control Problems of Ultra-Flexible Aircraft

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1. Introduction

For millions of years nature has developed flying by the pliable wings of the saurians, birds, and insects. Evidently the highly flexible wing is advantageous to living beings: it is at the same time an efficient wing and propulsion element, it has a variable geometry, which adapts itself the best way to the existing flight condition, and when there is no need for flying, it may be packed into a small bundle, carried on the back of the animal. No wonder that human beings tried to imitate the animals' flight equipment for centuries—without success. The breakthrough in human flight came only when the rigid wing was found. But the price for "rigid flying" is high. A lot of machinery, instruction, auxiliary equipment and money is needed, before a rigid flying machine can take off from some limited places on the earth.

In 1948 Francis Rogallo tried once more the simple way. He put two dinghy sails together, in order to form a symmetrical tailless wing, the "Rogallo Wing", which became airborne by foot launch and was controlled by weight shift. This reinvention of the hang-glider allowed one to take off from any hill with a wing that cost nearly nothing and could be packed away into the baggage boot, when not needed. Thousands of human beings aimed to "fly like a bird" with the hang-glider in the seventies—and hundreds had to pay it with their lives, as so many pioneers in former days, who had tried to emulate the birds' flight with ultra-flexible wings.

Windtunnel tests performed in Switzerland with original sized Rogallo Wings (1) revealed some instabilities at low angles of attack and highly nonlinear aerodynamic coefficients *(Fig. 1, Fig. 2)*. But the problem was the question: What do those coefficients mean for the pilot? An unstable wing means not necessarily an unstable flight, when there exists a low center of gravity as the parawings show, and the center of gravity of hang-glider is remarkably low beneath the wings. The "Neutral point theory" could not give an answer because of that and because of the highly nonlinear aerodynamic coefficients of a flexible wing in the critical angle of attack range. The procedure, to

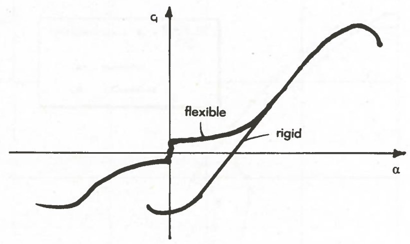

Fig. 1: Comparison of the lift coefficient of a flexible aircraft with a rigid aircraft.

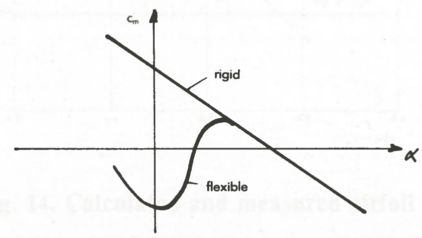

Fig. 2: Comparison of the moment coefficient of a flexible aircraft with a rigid aircraft.

derive the static stability from the slope of the curve, Moment Coefficient c_m versus angle of attack α did not help much more, because c_m has to be referred to the center of gravity of the whole system (glider + pilot); and where is the center of gravity of a weight shift controlled aircraft? How should a bunch of $c_m - \alpha$ curves enlighten the evidently existing irreversible dives?

Many questions remained because the conventional flight mechanics procedures were not relevant to the highly flexible aircraft. The author, himself a Rogallo Wing pilot since 1974 *(Fig 3)*, found the solution by introducing the "weight shift diagram" (2), (3), the findings of which have been recently extended by the author to the "stick displacement diagram" for the aerodynamically controlled ultra-flexible aircraft (e.g. ultra-lights), which suffer from similiar problems in their flight mechanics as the hang-gliders.

It has to be mentioned, that La Burthe in France copied or reinvented the weight shift diagram one year later, when ONERA tested in the big windtunnel of Meudon 10 hang-gliders (4).

Before analyzing the displacement diagrams and their applications, the deformation capabilities of the flexible aircraft will be classified and discussed.

Fig. 3: The author with his Rogallo Wing in 1975.

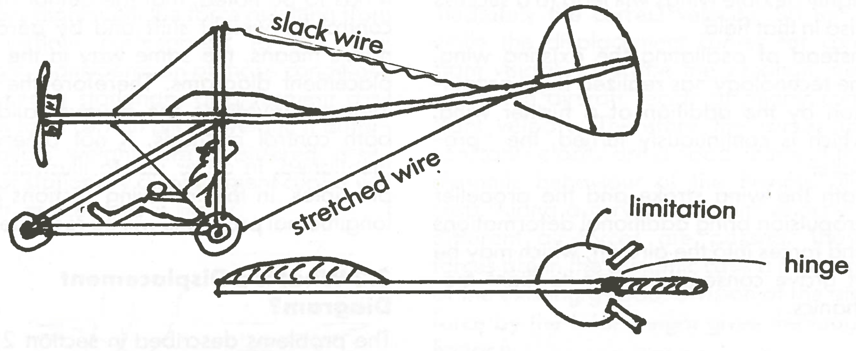

Fig. 4: Pseudoelastic deformation of an ultralight caused by slack connection wires. Above: physical, beneath: symbolic.

2. The Ultra-Flexible Aircraft's Deformation Capabilities

2.1. General

All wings undergo various deformations during flight. Those may be nonstationary (e.g. wing flutter) or stationary (e.g. elevator deflection), they may be self-acting (e.g. after a gust) or voluntary (e.g. by stick movement). The deformations may attain a confusing variety with the highly flexible wings. Therefore a classification of typical deformations is necessary for the understanding of the following sections.

2.2 The Self-Acting Aircraft Deformations

2.2.1 Pseudo-Aeroelasticity

The deformation of the conventional "rigid aircraft" is mostly of an elastic nature; the word for it is "aeroelasticity". But before entering aeroelastic deformations the highly flexible wing suffers a so-called "pseudo-elastic deformation". Let us consider an aircraft which has looseness in its connecting elements, e.g. slack connection wires *(Fig. 4)*. The aircraft's deformation does not depend on velocity, as it would for aeroelastic deformations, but only on the angle of attack. So the conventional aeroscience knows only the word "aeroelasticity" for self-acting deformations; the kind of deformation here described will be called "pseudo-aeroelasticity".
The deformation of a Rogallo Wing's sail is of the same nature. At high angles of attack the sail is blown up and behaves like a rigid wing *(Fig. 1, 2)*. But at low angles of attack the sail starts to luff and undergoes deformations, like those sketched in *Fig. 5 to 7*. Those pseudo-aeroelastic deformations were the reason for many hang-glider accidents in the past. The pseudo-aeroelastic Rogallo Wing may be modelled as symbolized in *Fig. 8*. In general the pseudo-aeroelastic effect is limited to a distinct angle of attack range. The limitation occurs, when e.g. a slack wire is stretched, or when the sail is blown up.

It has to be noted, that the term "pseudo-aeroelasticity" by definition means deformation of an aircraft, which depends only on angle of attack, not on velocity.

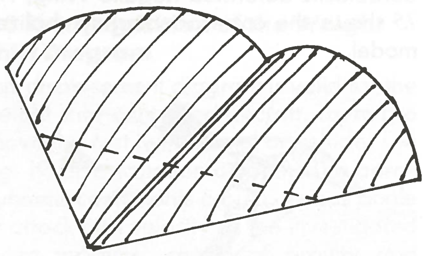

Fig. 5: The blown up Rogallo Wing behaves like a rigid wing.

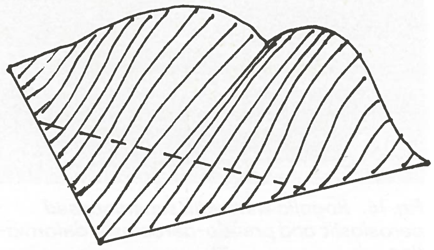

Fig. 6: The luffing sail at low angles of attack suffers under nose-heaviness because of pseudo-aeroelastic deformation.

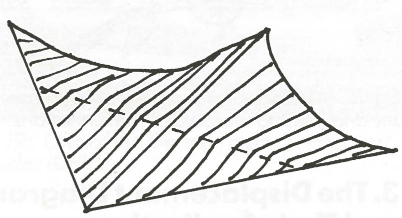

Fig. 7: The negatively blown up Rogallo Wing behaves like a rigid wing (severe nose-heaviness).

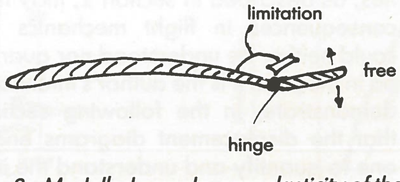

Fig. 8: Modelled pseudo-aeroelasticity of the Rogallo Wing, valid for positive angles of attack.

2.2.2 Aeroelasticity

Extended scientific work has been devoted all over the world to the aeroelasticity of conventional aeroplanes. Aeroelasticity, which deals with the elastic (Hooke's law) deformations of the aircraft, caused by the force of the air, is also valid for all ultra-flexible aircraft. The difference from the "rigid wings" lies in the fact that the aeroelastic deformations may be so high and important for the aerodynamics, that they can no longer be characterized as "linear". The typical aeroelastic deformation of a tailless wing is sketched in *Fig. 9*, the symbolized wing in *Fig. 10*. Aeroelasticity may be the cause of various problems in the flight mechanics.
It has to be noted, that the term "aeroelasticity" by definition means deformation of an elastic nature, which depends on angle of attack and velocity.

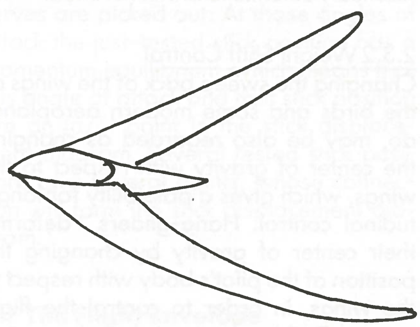

Fig. 9: Aeroelastic deformation of a tailless wing (severe stability problems)

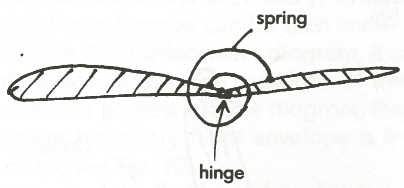

Fig. 10: Symbolized aeroelasticity of fig. 9.

2.2.3 Aeroelastic Buckling

Slender struts of an ultraflexible aircraft may buckle and lead to a sudden change in the flight stability. *Fig. 11* may give an impression about the flight mechanics problems that will occur, when a strut for the elevator control buckles.
It has to be noted, that the term "aeroelastic buckling", by definition, means deformations that start abruptly at a certain combination of angle of attack and velocity.

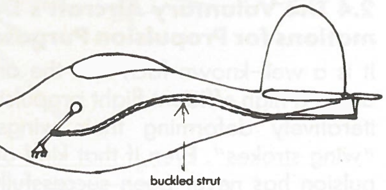

Fig. 11: Aeroelastic buckling of a control strut with ceasing contról efficiency.

2.3 The Voluntary Aircraft's Deformations for Control Purposes

2.3.1 Aerodynamic Control

It is a well-known procedure, to deform the aircraft by pilot's force, in order to get longitudinal or lateral control. The deflection of flaps by a control stick is mostly used. There arise problems, when the control efficiency is nullified or even reversed because of partial flow separation or secondary deformations like the "Flettner effect" *(Fig. 12)*.

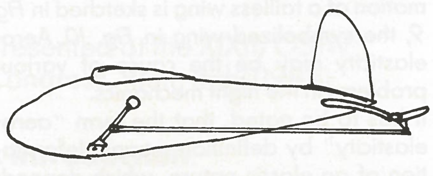

Fig. 12: Reversed control efficiency because of secondary deformations. (Flettner Effect)

2.3.2 Weight Shift Control

Changing the sweep back of the wings as the birds and some modern aeroplanes do, may be also regarded as changing the center of gravity with respect to the wings, which gives a possibility for longitudinal control. Hang-gliders "deform" their center of gravity by changing the position of the pilot's body with respect to the wings, in order to control the flight system. Problems arise, when the control force becomes too high, or when the control efficiency is nullified or reversed. *(Fig. 13)*.

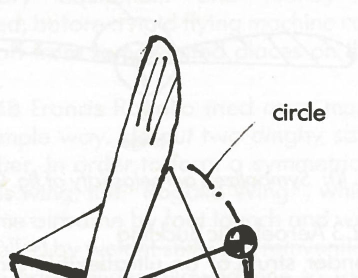

Fig. 13: Ceasing control efficiency in the dive of a hang-glider.

2.4 The Voluntary Aircraft's Deformations for Propulsion Purposes

It is a well-known fact, that the animals attain a high efficient flight propulsion by iteratively deforming their wings, the "wing strokes". Even if that kind of propulsion has never been successfully applied for human beings, the author expects that the further development of highly flexible wings will lead to a success also in that field.
Instead of oscillating the existing wing, the technology has realized flight propulsion by the addition of a further wing, which is continuously turned, the "propeller".
Both the wing stroke and the propeller propulsion bring additional deformations and forces into the aircraft, which may be of grave consequence for its flight mechanics.

2.5 Combined Deformations

All the above-described deformations may occur simultaneously; they are furthermore modified by the pilot's weight, because a heavy pilot causes a different deformation distribution within the highly flexible aircraft, from a light one. *Fig. 14* is a photo of an aeroelastic and pseudo-aeroelastic deformed Rogallo Wing; *Fig. 15* shows the corresponding symbolized model.

Fig. 14: Rogallo wing with superimposed aeroelastic and preudo-aeroelastic deformation.

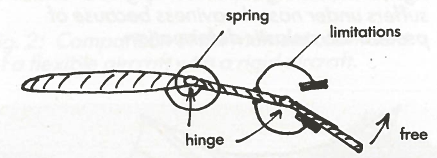

Fig. 15: Model of the superimposed aeroelastic and pseudo-aeroelastic deformations.

3. The Displacement Diagrams and Their Application

3.1 General

The superimposed deformation capabilities, as described in section 2, may have consequences in flight mechanics that could neither be understood nor quantified in the past. It is the author's intention to demonstrate, in the following sections, that the displacement diagrams enable one to quantify and understand the integral stability and control consequences of any deformation.

It has to be noted, that the author treats control by weight shift and by aerodynamic means, the same way in the displacement diagrams. Therefore the following derivations are always valid for both control methods, if not otherwise mentioned. In order just to illustrate the principles, in the following sections only longitudinal problems will be regarded.

3.2 What is a Displacement Diagram?

The problems described in section 2 demand consideration of the deformation problems and the control problems as a whole. Because the control action is characterized by a displacement of the controls (stick or weight), and because any aircraft's deformation has its required control displacements, in order to produce momentum equilibrium, one can say, that both the control efficiency itself and the deformations are reflected in the required displacement. In order to get a diagram: "Displacement versus anything", it is wise to take as the "anything" a variable, which characterizes in a distinct way the whole flight envelope. To take the velocity is not regarded as a good way, because it is an ambiguous parameter: The velocity polars reveal that there may exist for different flight states the same velocity. The only wanted parameter is the unequivocal angle of attack.
To summarize:
The displacement diagram is a plotted curve in the coordinate system: Angle of attack α versus displacement δ of the control. Displacement hereby means the required control movement (stick or weight) in order to obtain momentum equilibrium for the corresponding angle of attack. The question, in which dimensions α and δ have to be taken, is a question of definition and of secondary interest.
A typical displacement diagram (here weight shift) is plotted in *Fig. 16*.

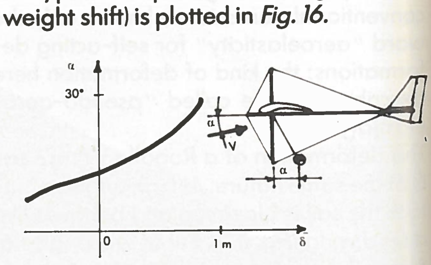

Fig. 16: A typical displacement diagram.

3.3 Stationary Displacement Diagrams

As mentioned above, the deformation of an ultra-flexible aircraft depends on velocity, angle of attack and pilot's weight. When the angle of attack is decreased, the velocity has to be increased in the stationary flight, until the force resulting from the airflow corresponds to the total weight. Consideration of those conditions leads to a stationary displacement diagram for a certain pilots' weight. If different pilots' weights are considered, a series of stationary displacement curves will result, as sketched in *Fig. 17.*

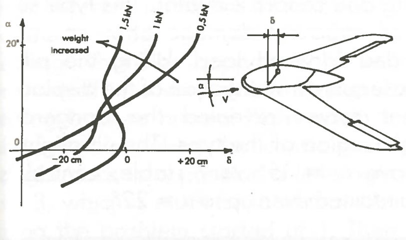

Fig. 17: Typical stationary displacement curves of an aeroelastic tailless aircraft.

3.4 Nonstationary Displacement Diagrams

Windtunnel or vehicle tests (see next section) are executed at constant velocities. Therefore it is advantageous first to plot displacement diagrams for constant velocity. Then the parameter points for equal air-force are picked out of these curves, and connected, which will give the stationary curves.

But the displacement curves for constant velocity have also a different meaning. When the aircraft suffers a sudden disturbance, it has not the time to attain immediately the correct velocity. So for a while the displacement curves for constant velocity describe the situation, because the aircraft reacts at nearly constant velocity. Therefore the curves for constant velocity are a good image of the dynamic behaviour of the flexible aircraft. Along a curve "constant velocity", different air-forces are passed. Those forces are in the dynamic case a measure of the existing g-load. Division of the air-force by the total weight gives the load-factor n.

In Fig. 18 a whole series of stationary and nonstationary displacement curves is sketched. For a completely rigid wing all curves would fall together! (Reynolds effects neglected). If not otherwise mentioned, in the following sections only stationary curves are meant.

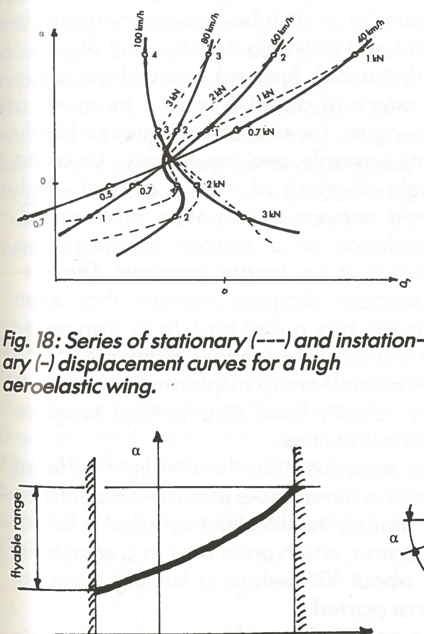

Fig. 18: Series of stationary (---) and instationary (-) displacement curves for a high aeroelastic wing.

3.5 The Acquisition of the Weight Shift Diagram

This displacement diagram is valid for the weight shift-controlled aircraft. There are known by test (windtunnel or vehicle, see *Fig. 19)* or calculation or both: The aerodynamic coefficients c_l, c_d, c_m versus angle of attack and velocity of the investigated flying machine, center of gravity and mass of aircraft and pilot and the kinematics of the allowed pilot's displacement

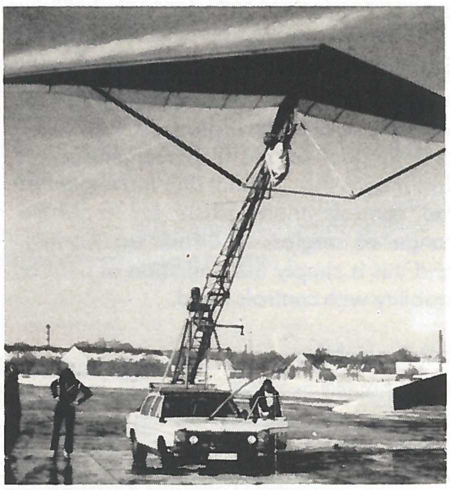

Fig. 19: One of the German aerodynamic test vehicles (DHV).

in order to control the aircraft by weight shift. Then for all angles of attack α of interest the necessary pilot's displacement δ for momentum equilibrium is calculated. All points (α/δ) are then plotted into the α-δ diagram and connected in the right way. The resulting curves give the weight shift diagram.

3.6 The Acquisition of the Stick Displacement Diagram

This displacement diagram is valid for stick-controlled aircraft. There is known by test or calculation or both for several different fixed stick positions: The aerodynamic coefficients c_l, c_d, c_m versus angle of attack and velocity. The moment coefficient c_m has to be referred on the center of gravity of the whole flight system, including the pilot. Then the zero prints of the c_m curves are picked out: At those angles of attack the just-tested stick position has a momentum equilibrium, which means that this angle of attack and that stick position are an (α/δ) point in the stick displacement diagram. Several tested stick positions give several points, whose connection will form the stick displacement diagram.

3.7 The Flight Envelope

The pilot in the air can only act on his aircraft by the controls. The effect of the control movement on the (stationary) flyable angle of attack range can be seen immediately on the displacement diagram, it is its definition. If the stop locations of the controls are plotted into the diagram, the complete stationary flight envelope is illustrated, see *Fig. 20.*

Limitations of the flight envelope because of instabilities or limited controllability are dicussed later.

3.8 The Controllability

3.8.1 The Control Efficiency

The slope dα/dδ of the displacement curve is an immediate measure of the aircraft's controllability. It says, how much the control has to be displaced, in order

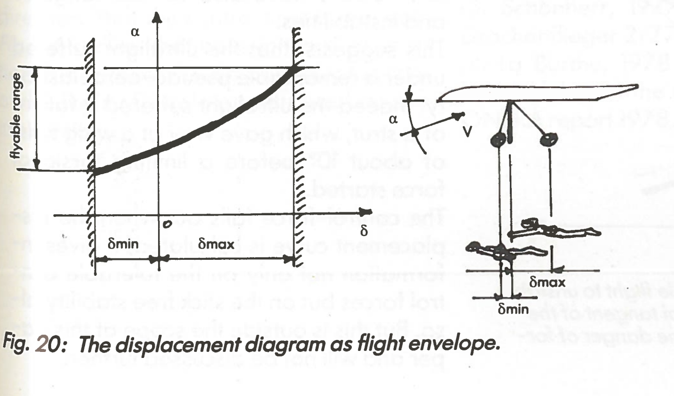

Fig. 20: The displacement diagram as flight envelope.

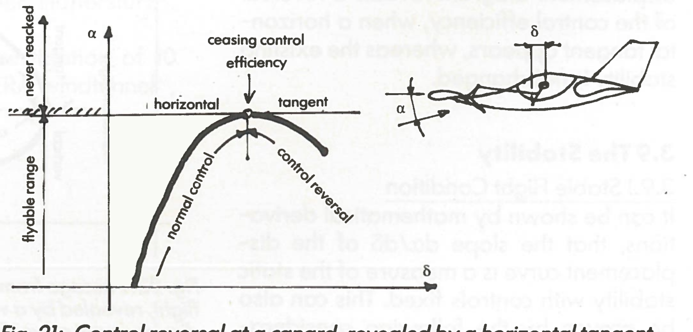

Fig. 21: Control reversal at a canard, revealed by a horizontal tangent in the displacement curve.

to obtain a certain change in the angle of attack. The sign of the displacement is defined, that reward movement of the stick or of a weight has the positive sign. Thus a right hand inclination of the displacement curve means a normal control behaviour: Pulling on the stick means moving on the curve and the angle of attack increases.

3.8.2 Ceasing Control Efficiency

If $d\alpha/d\delta$ becomes zero, there exists a horizontal tangent in the displacement diagram. The control efficiency has become zero. This will be true for the flexibility problems, sketched in *Fig. 11* and *12;* the problems will occur at higher velocities and low angles of attack. But loss of control efficiency may also happen because of aerodynamic reasons, as illustrated in *Fig. 21.* This shows a possible displacement diagram for a canard plane with the elevator on the front wing. When the highly loaded front wing is made to give more and more lift because of increased elevator deflection, then the front wing may suffer a flow separation, and further rearward stick movement will not bring up the nose any more. It is suggested, that this is the "Quickie problem", and that its displacement diagram looks like *Fig. 21.* This aircraft had severe flight mechanics problems when flying through rain. Evidently its front wing suffered in that case an early flow separation, which leads to the problems described above.

Be it a flexibility problem or a flow separation problem: Loss of control efficiency reveals in the displacement diagram, that there exist angle of attack ranges, which can never be attained; the flight envelope has to stop there!

3.8.3 Reversed Control Efficiency

After having passed a vertical tangent with loss of efficiency, the control suffers a reversal of the efficiency. This means for example in the above canard case (Fig. 21), that more rearward stick movement results in less angle of attack, as the left-hand inclination of the displacement curve reveals. It has to be noted, that the displacement diagram reveals a reversal of the control efficiency, when a horizontal tangent appears, whereas the existing stability is not changed.

3.9 The Stability

3.9.1 Stable Flight Condition

It can be shown by mathematical derivations, that the slope $d\alpha/d\delta$ of the displacement curve is a measure of the static stability with controls fixed. This can also be proven by the following considerations, see Fig. 22:

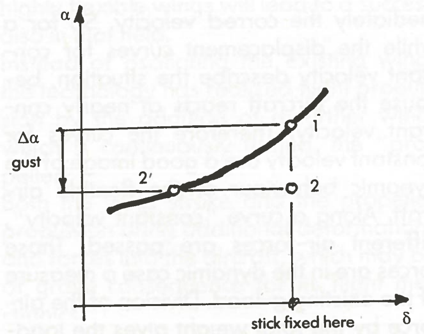

Fig. 22: To explain, that right-hand inclination of the displacement curve means stability (see text).

Let us assume that the initial condition of a stick-controlled aircraft is at point 1, and the pilot will keep the controls fixed. Then comes a sudden downgust, which brings the angle of attack to the lower position 2. The displacement curve shows, that for equilibrium the position of the stick has to be reduced from position 2 to 2′. However, the pilot keeps the stick fixed at the old position, which means that he pulls more than the position 2 requires. Therefore the reduced angle of attack will return to its old value 1. So we see that when there exists a right-hand inclination of the displacement curve, and the stick is fixed, a recovery of the disturbed angle of attack will occur. This is just static stability with controls fixed, as we wanted to prove.

3.9.2 Neutral Flight Condition

If $d\alpha/d\delta$ becomes infinite, we have no longer a right-hand inclination, but a vertical tangent on the displacement curve. This means that without any movement of the controls there exists for a whole range of angles of attack equilibrium, and this is simply the definition of neutral stability with controls fixed.

3.9.3 Instability

After having passed a vertical tangent, the displacement curve becomes left hand inclined, which means instability with controls fixed. This can be proven the

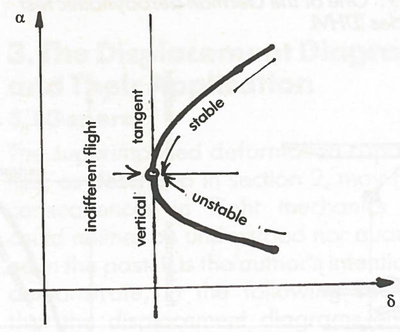

Fig. 23: Passage from stable flight to unstable flight, revealed by a vertical tangent of the displacement curve. Extreme danger of forward loop!

same way as in 3.9.1. *Fig. 23* sketches the displacement curve of an aircraft which suffers a passage from stability to instability.

This displacement curve reveals reversal of the flight stability, when a vertical tangent appears, whereas the control efficiency is not reversed.

Fig. 24 shows an ultralight with swepted wing and canard elevator. This type suffered structural damage after an unintended forward loop, kllling the pilot. Subsequent investigation of the displacement curves revealed the dangerous flight region of the type. The ultralight is above $\alpha = 15°$ very stable; control is maintained even up to $\alpha = 22°$.

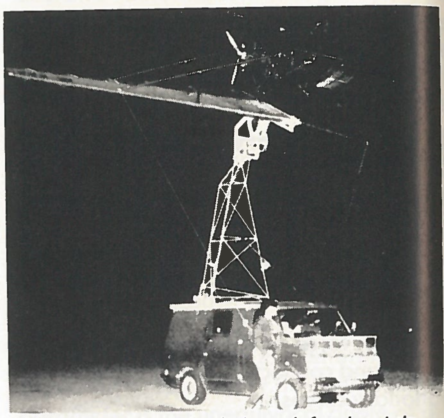

Fig. 24: Test of an ultralight with fatal stability behaviour.

But near $\alpha = 10°$ and maximum forward stick position it has a vertical tangent, which means that it becomes neutral and around $\alpha = 0°$ it becomes very unstable (left hand inclination). If the pilot flies fast with the stick forward and with an angle of attack of about 5° and if he meets a downgust, the aircraft becomes suddenly very unstable and noseheavy. Once an angle of attack of $-10°$ is passed which might happen in less than one second, avoidance of a sudden forward loop ("tuck") is no longer possible. The displacement diagram reveals that even with the stick pulled back to its stop noseup moment is no longer obtainable.

The nonstationary displacement curves at low velocity have also vertical tangents and instabilities.

This suggests, that the ultralight suffered under a remarkable pseudo-aeroelasticity. Indeed the ultralight suffered a failure of a strut, which gave way at a wing twist of about 10° before a limiting torsional force started.

The control-force falls out when the displacement curve is calculated; it gives information not only on the tolerable control forces but on the stick free stability also. But this is outside the scope of this paper and will not be discussed further.

3.10 Hysteresis Effects

The highly flexible aircraft with low center of gravity may have the pecularity that it becomes unstable at low angles of attack but becomes stable again when approaching zero lift. The stability changes behave like a hysteresis effect, which the displacement diagram reveals (Fig. 25). The pilot, who puts his control position (or his body) to a region a little left from 1, meets a sudden nose-heaviness and instability. Before knowing what has happened, he will find himself in a very stable dive in 2. Coming back to normal flight again is only possible, when the controls are brought back to a position a little right from 3, which is much beyond that obtaining the problem started at 1. Then the flight will return to the stable phase at 4. The encircling of the area 1-2-3-4

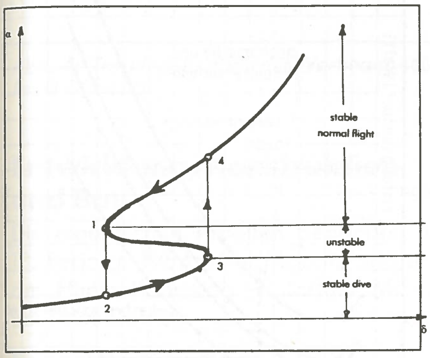

Fig. 25: To explain the hysteresis effect in dives (see text).

is a hysteresis effect, and one of the reasons that entering a dive may be much easier than coming out of it. Indeed surviving luffing-dive pilots have reported that the controllability in the dive is nearly zero (very flat curve between 2 and 3), and that they had to bring their body very far back, in order to get out of the dive, which happened "with a bang" (unstable recovery between 3 and 4).

3.11 Irreversibilities

The hysteresis effect above described may be so extended in the displacement direction, that the control limit is reached. *Fig.* 26 shows, that once in the dive position 2, a recovery is not possible; the dive of the highly flexible aircraft has become irreversible.

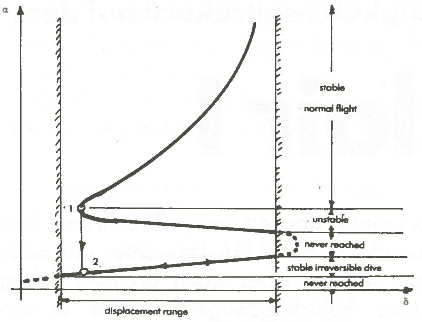

Fig. 26: To explain an irreversible dive (see text).

4. Outlook

Since 1975 the author has investigated about 800 versions of all kinds of hang-gliders and ultralights for the official certification in Germany. Only some spectacular cases have been presented in this paper. The vast majority of the current hang-gliders have passed vehicle testing and have been analyzed by displacement diagrams; it has been proven, in a million flights, that the flexible aircraft has now obtained a remarkable safety standard.

The very promising aim of the future are not to beware of high flexibility, but to take more advantage of it. A designed flexibility helps for better control and performance. What the rigid wing tries to obtain by an expensive variable geometry, the flexible wing achieves at no cost. Therefore the author would not wonder, if hang-gliders one day reach the glide ratios of the sailplane–by the muscle-powered wing stroke principle. Unlike former days the necessary safety instruments are available today.

References

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Summary

The conventional procedures for the stability analysis of aeroplanes do not suit the ultra-flexible aircraft (hang-gliders, ultralights), because of the non-linearity of their aerodynamic coefficients, and/or because they are controlled by weight shift, which means that they have an always changing centre of gravity. The solution brought the author's introduction of the "weight shift diagram", which first permitted understanding the limited controllability and irreversibility of the dives of the hang-gliders. If the criteria of the weight shift diagram are transferred to the "stick displacement diagram", the stability behaviour of aerodynamically controlled ultraflexible aircraft also can be determined. The inclination of the curves is a direct measure of the stability and controllability. If there exist horizontal tangents, they indicate a reversal of the control efficiency; if there exist vertical tangents, they indicate a reversal of the stability. It is possible, to localize the reasons for the reversals, and to find out, if they are of aerodynamic nature (flow separation) or if they result from a deformation in a flexible structure.