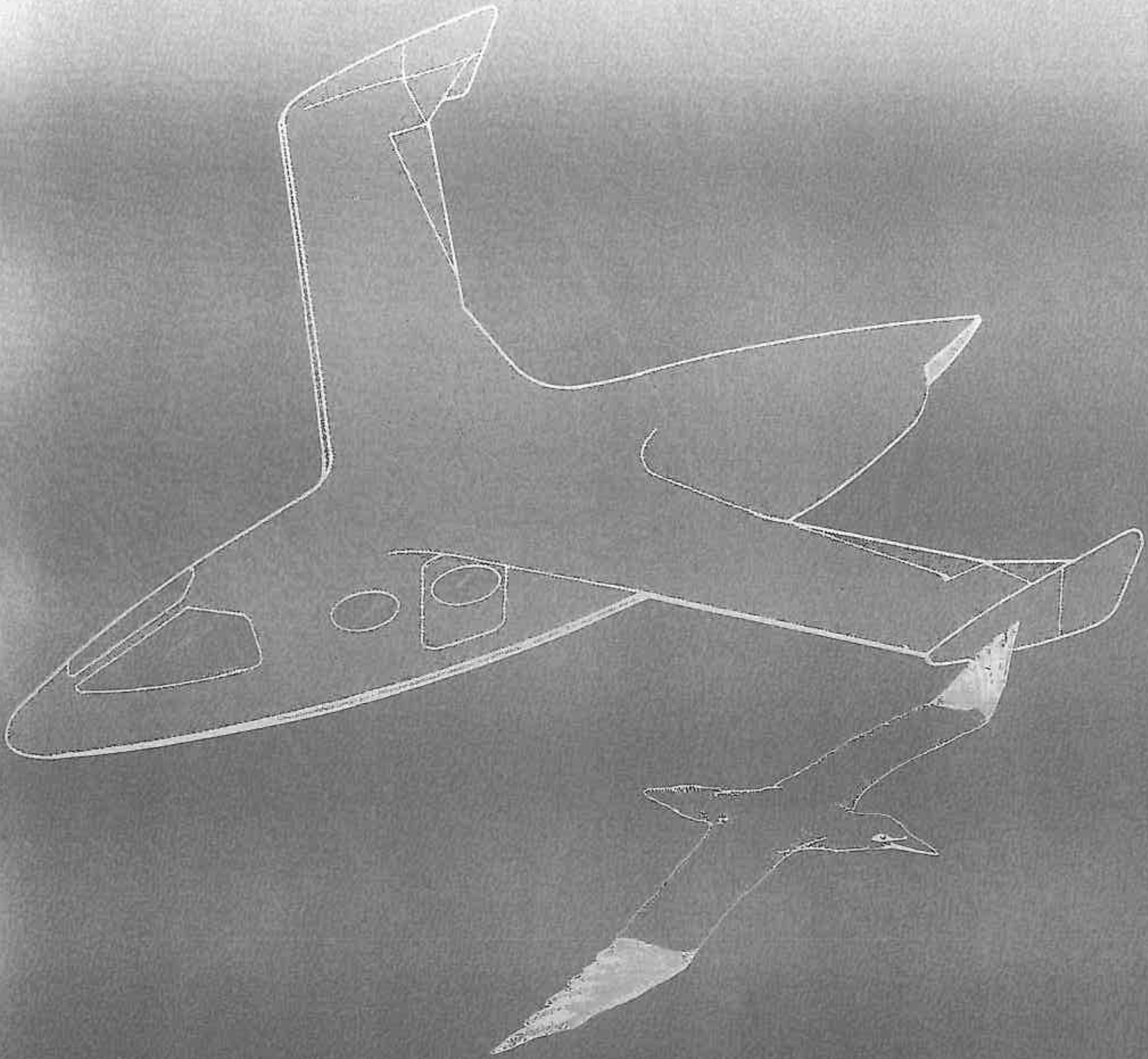

THE KASPER WING

by Witold A. Kasper

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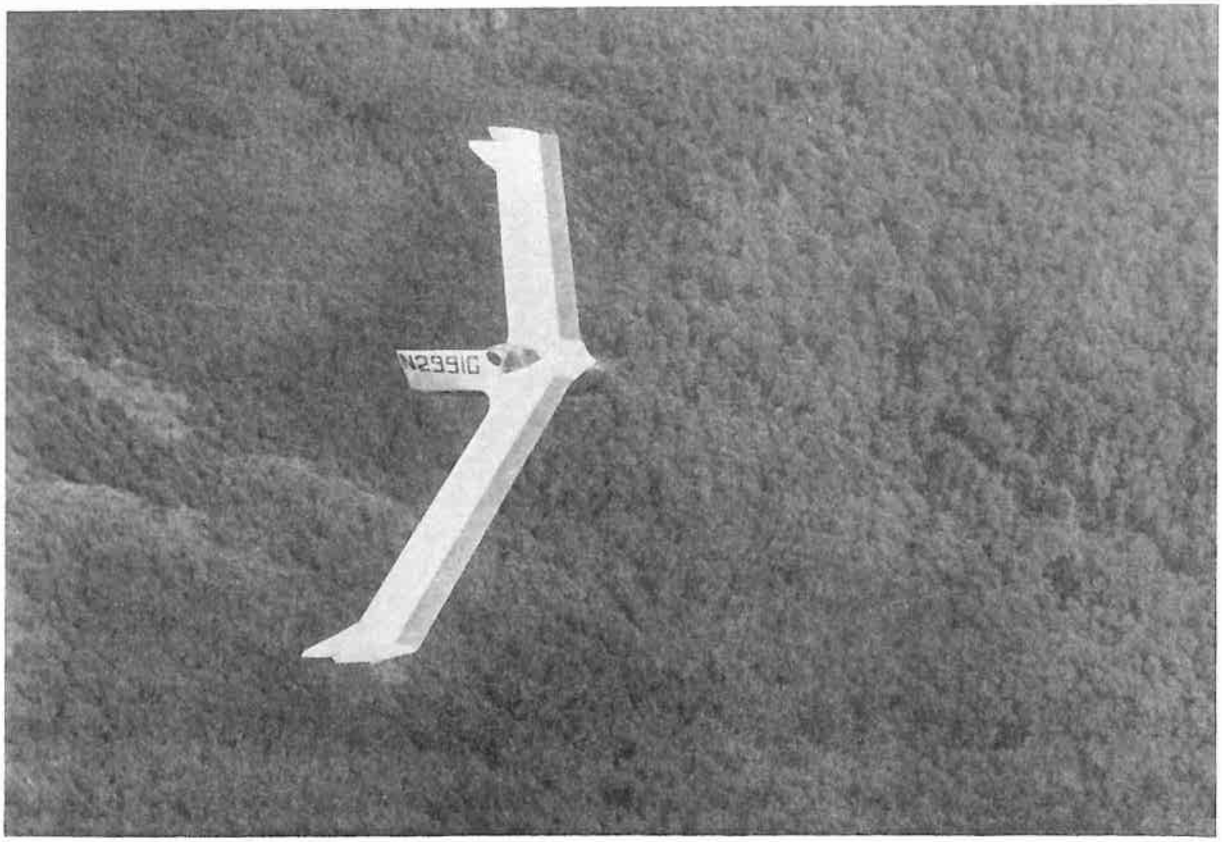

The author in his BKB-1 soaring over the Cascades.

Witold A. Kasper

THE KASPER WING

by Witold A. Kasper

Edited by: H. Joe Meheen
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FOREWORD

This year is the 75th anniversary since man first took to the air in a heavier than air machine. In one man's lifetime we have advanced from the Wright Brothers' first crude powered vehicle to today's jet powered airplane which flies beyond the speed of sound. Man's early attempts were patterned after bird flight. But to this date no one has been able to duplicate the maneuverability, safety and slow landing speed of the bird. In the race for higher and higher speeds, the aircraft designer has neglected this phase of aeronautical knowledge. The modern Rogallo type, low aspect ratio, flexible wing hang glider probably comes closer to bird flight than any other type of aircraft available in today's market place.

Aircraft designers realized early that a tailless aircraft came closer to the configuration of a bird. However until the discoveries by the author of this book nobody had detected the secrets with which Nature has equipped the bird.

Lippisch in Germany, Hill in England, Fauvel and Horten, Kaniewska and Sandauer in Poland and Jack Northrop in the United States all designed flying wings. But none succeeded in solving the basic secret of slow flight with full control which is not dependent upon the forward speed of the aircraft. Such a discovery would eliminate the concept of "stalling speed."

As the result of a lack of understanding of the aerodynamic phenomenon involved in bird flight, a number of capable pilots lost their lives and a general distrust of tailless aircraft swept the aeronautical world. The cross-tail was born and was accepted as the "Universal Band Aid" for aerodynamic lack of knowledge.

The author of this book, Witold Kasper, was born in Poland, obtained his Masters degree in Mechanical Engineering in Zurich, Switzerland and his Masters Degree in Aeronautical Engineering in Poland. He was a pilot in the Polish Air Force before World War II and a leading soaring pilot who headed Poland's Olympic Soaring Team in 1939. He is an ardent student of bird and insect flight since childhood.

The Random House Dictionary defines discovery as follows: DISCOVER, INVENT, ORIGINATE suggest bringing to light something previously unknown. To discover may be to find something that had previously been in existence but had hitherto been unknown.

To invent is to make or create something new, especially something ingeniously devised to perform mechanical operations.

These definition tell us exactly what Kasper is and what he has done. He began to put his discoveries on paper in 1939 but World War II put a temporary stop to his research. He designed and built his BKB-1 tailless glider in 1950 in Canada and received a Canadian Airworthiness Certificate for it in October 1959. The machine was brought to Seattle when Kasper moved to the U.S.A. and joined Boeing Aircraft Company in February, 1958.

The first flight in the U.S.A. was made by a Boeing Engineer by the name of A.G. Wilson. Kasper made his first flight in America in November, 1963. The years between 1959 and 1963 were spent in improving, testing and flying the BKB-Flying Wing. On June 28, 1965, F.A.A. issued its Certificate of Airworthiness for Kasper's Flying Wing. This certificate included aerobatics and embraced TUMBLING.

The formerly dreaded tumbling gyrations of Flying Wing designs were harnessed by Kasper, as demonstrated by him at various Air Shows in the Seattle area. His aerodynamic wingtip controls always remain fully effective and are successfully employed to initiate, to control and to stop tumbling.

On April 12, 1968, Kasper flew his BEKAS-N Flying Wing on its initial flight. This was an improved high performance sailplane which Kasper believes allowed him to soar dynamically on horizontal gusts.

The United States Patent Office issued patents on his aircraft designs in April, 1969 and in August, 1974. He received his patents on vortex generation on aircraft. His original research in this field is well known to Aerodynamicists both here and abroad. The application of this discovery in Flying Wing design results in extremely high lift coefficients, less drag and reduced power requirements.

Currently available technical data on the behavior of Flying Wings are fairly old, most of it dating back to the early 1930's. I am very grateful to my friend Witold Kasper that he is willing and generous enough to share with aviation enthusiasts his discoveries of slow flight with safety. His explanations of controlled flight in deep stall by aerodynamic means and independent of forward speed, and his theory of stability are alone worthy of acceptance by the aeronautical community. Every student, every pilot and every aircraft designer will benefit from this. The road is now open for the advent of a safe air vehicle.

Thank you Witold, and thank you Mr. Publisher, who have made this possible.

Kauai, Hawaii, December, 1978
Agne T., "LU" Lundgren

Bellevue, Washington

1 April, 1979

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INTRODUCTION

Man's interest in flying goes back many thousands of years. It was triggered by observing the birds, which have a far superior mobility than man has ever been able to achieve. The capability of moving in three dimensions created the urge in man to fly. The first attempts were made by the Chinese by using kites, which were developed up to the capability of carrying a man. We know now that kites were used to drop soldiers into fortresses, very much as the modern paratroopers do. However the Chinese never advanced to untethered flight.

The urge to fly like a bird was expressed in "fairy tales" or legends like the one about Icarus and Daedalus. In those legends man imitated the BIRD. Later when man's knowledge and technology improved, men like Leonardo da Vinci tried to solve the puzzle of the bird's flight. Recognizing the complexity of the bird's system, they tried to replace it by a man-conceived mechanism. For propulsion the wing flapping was replaced with a propeller, but for lift the wings were retained. Because the early flyer was unable to solve the mystery of pitch, roll and yaw control we had to wait a few hundred years before man could become airborne.

The first flight was achieved only a hundred years ago by Otto Liliental. He also used the bird as his model. Apparently he solved the puzzle of the stability and control of birds without substituting different man-made contraptions: his flying record proved that his glider was safe. Without knowledge of aerodynamics or flying training by an experienced flight instructor, he was able to make thousands of flights just like a young bird. The superior design of his "machine" brought the novice flyer safely in for a landing, just like a chick who for the first time is pushed out from the nest by the mother bird. We see young birds, without flying lessons, spread their wings and glide clumsily but safely from the tree to the ground. Apparently the system they are using is very effective, as far as safety is concerned.

The first powered flight recorded by man was made by the Wright brothers. They also built a wing like the bird's wing. To make it strong enough, they used a biplane configuration. When they installed the heavy engine, they found that the plane was nose heavy, so they logically provided the nose with a third wing and thus the canard configuration was invented. This was the first deviation from nature, and they paid for it. Today we know the disadvantages of the canard configuration: incapability of inverted flight, and limited maneuverability. The capability to tolerate greater CG movement, and slow speed controllability are the advantages of the canard.

When the military became interested in aircraft, the needs of warfare called for the capability to do acrobatics and inverted flying, for which the canard system was particularly unsuitable. Instead of taking another look at Nature's design, the bird, which has abundant maneuverability, the designers followed the wrong path. They added a crosstail which the bird did not have. They achieved their goal of maneuverability but for a price.

Because the plane's center of gravity (CG) is forward of the center of lift (CL) and the tail is in the rear, the forces on the tail have to be directed downward, which loads the wings additionally, decreasing the payload. This is especially critical during flare out for landing when the need for maximum lift is the greatest. This is the reason why some heavily loaded planes are not able to land with their full take-off weight and must dump fuel in order to lighten the plane.

Another disadvantage of the crosstail configuration is that the wing must be built stronger in order to resist the bending and torsional moments created by the tail. This results in a heavier wing which again cuts down the payload.

The forces generated by the tail are aerodynamic forces which are proportional to the second power of speed. The control forces increase and decrease with V^2. Control is lost when the speed is insufficient to generate the needed forces. This minimum speed is called "minimum control speed." Flying below this speed means loss of control and when this happens, at take-off or landing, in the majority of cases the plane crashes. Consequently the rule is, "Never fly below the minimum control speed." This means safe landings require a minimum forward speed. The birds land at zero forward speed. They do not need a runway. We cannot achieve this with our control system, so we have to fly in at high speed and touch the runway and continue running until the plane slows down and becomes an earthbound vehicle and can eventually come to a full stop.

The "minimum control speed" limits our flying angle of attack to 12-20°, to remain above the so-called "stalling speed" at which the smooth flow of air over the wing separates and lift drops suddenly. Birds fly and land at angles of attack of up to 90°. This means vertical "mush" while maintaining lift, control and stability. How do they do it? What happens to the lift past the stall? We pilots don't know because we have never experienced it, not being able to fly at high angles of attack and below stalling speed.

Very interesting wind tunnel tests were made in 1955 when NACA tested a wing, at all angles of attack, by turning the model 360°. The tunnel tests were not limited by "minimum control speed." Those tests show clearly that the so-called stall disappears after the stalling angle is passed. The lift starts again, smooth and without interruption. However no one became seriously interested in this phenomenon. We are still limited to about 20° angle of attack and the "minimum control speed."

The birds are apparently using the phenomenon, proven by the tests, which allows them full control past the stall, up to 90° angle of attack and landing at zero forward speed.

During the past 50 years many improvements have been made to the airplane in order to eliminate the undesirable properties. There has been a move to go back to the "bird" configuration, the flying wing. Unfortunately the designers were former tail-plane designers and they applied their theories to the tailless flying wing design. Instead of starting a completely new way of thinking, and incorporating as much as possible of the bird in the prototype, they used solutions from the crosstail design which were detrimental to the tailless wing and created new problems.

At the same time that aeronautical sciences were progressing, much research was initiated by other branches of science into the mechanics of bird flight. High speed photography helped considerably. Unfortunately very few aircraft designers and aerodynamicists were interested in the research done by zoologists, biologists and some nature lovers. It is fascinating as well as informative to see how Nature solves the problems of aerodynamics, stress, stability and control. Millions of flying creatures such as birds, insects, mammals and fishes would have become extinct without fail-safe and efficient flying systems.

This author started flying in 1934. I won the gliding championship in Poland in 1937. As an accomplished pilot with 600 hours of flying time, a Bachelor of Science in aerodynamics, and an instructor, it disturbed me greatly to see so many senseless accidents, due to loss of control, which caused injuries and fatalities.

While flying sailplanes in the company of birds I noticed their uncanny capabilities which current knowledge could not explain. I decided to study the birds and apply their system to man's flight. Most noticeable was that no bird had a crosstail. Some birds do not have a tail at all and still can fly and maneuver perfectly. The birds with long tails such as peacocks and male pheasants are not very maneuverable flyers. It appears that long tails are detrimental to good flying.

The next step was to study the previous all-wing designs. Here I found that while some designs had better qualities than the crosstail plane they had other undesirable properties which the bird did not have. Apparently the tailless wing designers were still contaminated with the standard solutions used in solving problems of control and stability for the crosstail airplane designs. They ran into similar difficulties and limitations which are plaguing our conventional airplanes. A completely new approach was needed. I decided to design an airplane as close as possible to the bird configuation. I knew that I would have difficulties because I could not duplicate the flexibility of the bird design, but I could find out what the birds were doing aerodynamically and produce the same effect with different mechanical solutions.

Recognizing that these new ideas challenged existing theories on the design of airplanes and very little outside help could be relied upon, I decided to experiment alone.

The most economical and effective method to test my theories was to design a birdlike glider which was not affected by a propeller and could use the free atmosphere as a wind tunnel. Thus the BKB-1 glider was designed, built and flown.

I KASPER WING VS. CONVENTIONAL DESIGNS

To compare the flying characteristics of the airplane and the bird was the reason for building and testing the Kasper Wing glider.

The glider was conceived with the purpose of obtaining a Flying Wing with the stability and controllability approaching those of the bird. The following pages will outline the differences between the airplane with the crosstail and the bird with the tail folded or even with no tail at all.

1. The airplane's low speeds are limited by the minimum control speed and the so-called "stalling speed," below which the airplane ceases to be a flying machine.

   The bird does not have any speed limitation to be able to fly.

2. The airplane functions within a 20° angle of attack while the bird's operating range extends up to 90°. This is best demonstrated at landing when the bird comes to a full stop at an incredible angle of attack and gently settles down, under full control, to a pinpoint landing. The birds are also able to circle in currents, in a nose high attitude well above a 20° angle of attack, the maximum stalling angle of airplanes.

3. Under maneuvering loads, including pullups, the loads on the airplane wings are increased and the wings bend up. At this time maximum bending moments and maximum torsional stresses are developing in the airplane wings. In order to withstand these combined loads, the wings have to be built much stronger, and consequently heavier, than would be needed for normal level flight when they have to withstand only the forces of nature, the air gusts. In order to reduce the stresses, the wings have been tapered to obtain a triangular load distribution. This decreases the bending moment at the root by about 17%. However, a penalty is paid, with a lift distribution which is far from the ideal. The wing efficiency drops to about 70% that of an elliptical planform.

   The bird wings can only withstand bending moments. They have no torsional stiffness at all, and a strength of only 3.5 G. Measurements have shown, however, that birds can pull out at 9 G's without their wings breaking off. The top plan of the bird wings show that not only are the wings not tapered, but they are wider at the tip than at the root. This causes a lift distribution more rectangular than elliptical, which increases the wing's efficiency to 100%.

4. The pitch and directional stability of our airplanes are linear functions and therefore require damping forces. Without them there would be constant oscillation. The damping is produced by forces on the crosstail generated by forward speed. When the speed is reduced the damping forces decrease until they are insufficient to return the airplane to the attitude which existed before the disturbance occurred. As a result the stability and controllability of the airplane decrease with reduced speed and limit its operating range.

   The bird's pitch, yaw and roll stability is based on a stable second degree system and increases with decreasing speed; therefore the bird can hover fearlessly before setting down to a pinpoint landing.

5. In order to decrease the landing speed of our airplane by increasing lift, the designers are changing the shape of the airfoil, adding flaps on both ends of the cord, sometimes adding suction or blowing, and increasing the wing area. At the same time, to counteract the nose down moment created by the downward deflected rear flaps, the stabilizer is inflected upward to create the compensating nose-up moment by generating a down force on the horizontal control surfaces. In other words, the wings are provided with complicated systems in order to increase lift, and the tail is loading the plane down, not to speak of the increased drag. This procedure does not seem to be very logical.

   The bird spreads its tail at landing and moves it downward, which produces additional lift. *What keeps the nose up when the speed is nearly zero?*

6. When the airplane is flying level, the forces on the tail are still present as download and drag, added to the weight of the tail structure. The drag due to the interference between the horizontal and vertical control surfaces often reaches 30% of the total drag of the airplane. When tail controls are used, they transfer their forces to the fuselage, bending it and twisting it. Therefore the tail surfaces create additional stresses in the wing and fuselage requiring heavier structures. The birds have no controls on the tail, so their bodies are stress free and no additional down load or drag is produced. The lift created by wings can be used 100% to carry both the bird and an additional load which often amounts to more than twice the bird's weight. Our airplanes have a ratio of payload to empty weight of 60%, the bird's ratio is 120% and more, with 30% less drag.

Described above are the obvious differences between the crosstailed conventional airplane and the BIRD. These differences must be understood by the serious airplane designer if he is going to produce an efficient and safe airplane. It is unfortunate that so much erroneous information relating to the tailless plane is being circulated in technical and semi-technical publications. Most of such data is based either upon hearsay or on obsolete data. Most of these data were based upon the knowledge that existed forty years ago. It is my hope that the result of my own experiences, research and flying will aid future designers in designing better and safer Flying Wings.

As a pilot, with thousands of hours of flying, from sailplanes to airliners, I decided to study and search for a solution to the safety problem. Being also an aeronautical engineer and aircraft designer, I had the advantage to be able to avoid the problem of communication among the three specialties. The main factor of success is to recognize from the beginning that the Bird Designer is far superior to any aircraft designer. I started with the study of bird's design and bird's flight. Often, when I encountered apparently impossible phenomena which were violating known aerodynamic laws, I decided that those laws were incomplete and applicable only to the very limited capabilities of our conventional airplanes. Theories need to be extended and improved in order to explain the bird's capabilities. No laws are rigid. They are valid at the time they are conceived, and change continuously as the technology progresses.

For example at one time the speed of sound was considered an unbreakable barrier, impossible to cross according to the subsonic rules. But then the barrier was cracked and new supersonic aerodynamics had to be learned and new rules had to be discovered. The new laws did not make the subsonic aerodynamics obsolete. They remained valid but were restricted within certain limits beyond which the new formulas were applicable. We cannot close our minds to observed phenomena because we cannot explain them. Our duty as scientists is to formulate new laws which will enable us to explain our observations.

Test flying the BKB-1 glider was not a problem. I did not need a special test pilot, nor high insurance to cover the risk. When flying it I experienced such a different behavior that, in spite of my thousands of hours of flying time, I had to learn whole new techniques.

The main differences in flight behavior were as follows:

> The glider could not be stalled, even when flown at an angle of attack of 40° to the relative wind.
>
> Lateral, longitudinal and directional controls were effective and solid at airspeeds down to 15 mph (the calculated stalling speed being 42 mph).
>
> The glider could be tumbled backwards and forward and recovered at will.
>
> It could be landed like a parachute with only 15 feet roll after touchdown without assistance from headwind or brakes.
>
> It did not have "dynamic stability." Instead it showed an uncanny stability, returning to the initial position within half an oscillation when disturbed by a gust or by the pilot.
>
> It could hover for eleven seconds.
>
> Turns could be made at a pitch angle of 45° without falling off on one wing.

After several years I was able to define the new rules of aerodynamics and become familiar with the new phenomena which would explain the strange behavior of this airplane, which is most natural for birds.

In order for pilots, scientists and laymen to understand the birdlike behavior of Kasper Wing design it is necessary to revert back to basic aerodynamic principles.

The following chapters will explain the principles of bird's stability, control and lift.

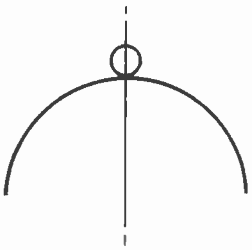
II STABILITY

The definition of STABILITY in a system is the ability to return to its original position when abruptly displaced. Stability is further explained as follows:

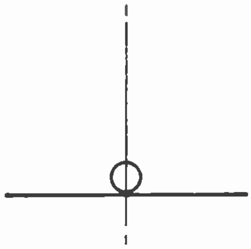
A. When a body resting in a position is moved by external forces to a new position and the external forces are removed, if:
   1. The body continues to move away from the original position, the system is unstable.
   2. The body remains in the new position, the system is indifferent.
   3. The body returns by itself, without the help of external forces, to the initial position, the system is stable.

This is the physical definition of STABILITY.

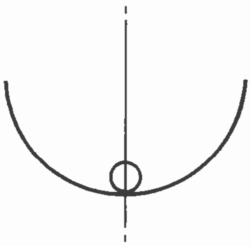
B. The three stability conditions are explained graphically by the engineers in Figures II-1, II-2 & II-3.



unstable
II-1



indifferent
II-2



stable
II-3

As we can see the first two conditions are true, but the example for the stable system (Fig. II-3) does not fulfill the requirements of the definition. The body will pass through the zero position at maximum speed, swing to the other side, stop and start moving back again. When external forces are absent (friction, air resistance, etc.) the body will never come to rest in the zero position. This means that this example does not represent a stable system. It is an oscillating system. Now, why this system was accepted as a stable system is a mystery. It could be that the engineers, as practical men, did not care about pure science, so they changed the definition to suit their purposes.

"A stable system is when the body, moved by external forces from the zero position, will show a TENDENCY to return to the origin and with help of friction or air resistance will finally stop at the initial position." They call it "dynamic stability." But when an object is stable it is at rest, and in Greek *dynamic* means *movement,* therefore it is a "moving rest," or a "stationary movement." Why not call it what it really is: an "oscillating stability," and when there is damping by external forces, call it "dampened oscillation."

C. At the outset it does not appear important whether oscillation is considered a stable system. But in reality it has caused great harm because it has delayed the search for a truly stable system. When everybody, from high school to university, is told that a pendulum is stable, he will never look for a really "STABLE" system.

When this discrepancy is explained to fellow engineers, their next question is, "But are there any systems which will fulfill the physical definition of a stable system?"

The answer is, "Yes, there are many stable systems which require neither external forces nor twisting the definition." Here are some of them (Figures II-4, 5 & 6):

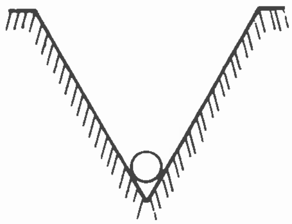


Fig II-4

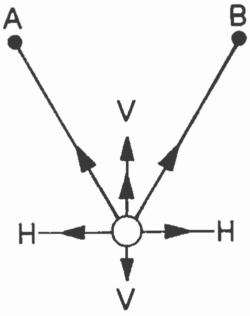


Fig. II-5

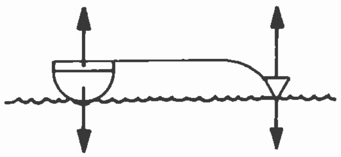


Fig. II-6

Since we are especially interested in stable systems, it will be useful to recall the mathematical definition of a stable system:

A system is stable when the sum of the forces acting upon the body in all three axes is zero and the sum of the moments around the possible movement epicenter is also zero. The forces have to be finite and cannot be zero.

Figure II-7

$$\begin{array}{ll} \Sigma X = 0 & \Sigma Mx = 0 \\ \Sigma Y = 0 & \Sigma My = 0 \\ \Sigma Z = 0 & \Sigma Mz = 0 \end{array}$$

Let us check the system claimed to be stable for the fulfillment of requirements in Figure II-7. First consider the system based on the pendulum:

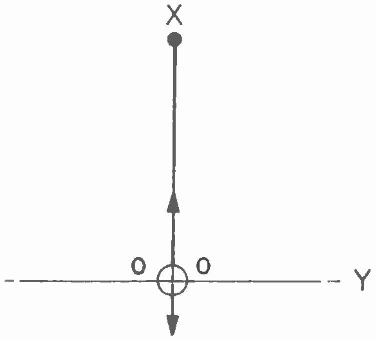


Fig. II-8

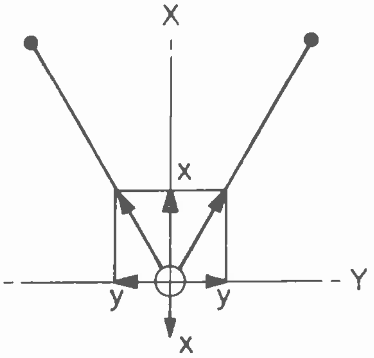
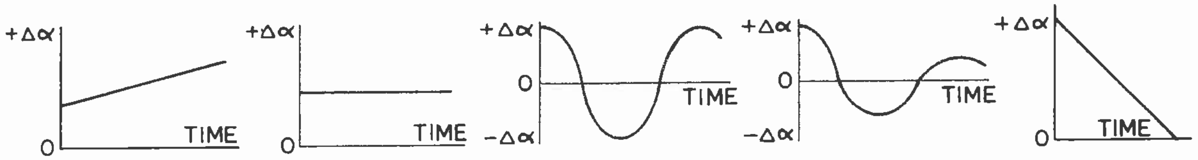


Fig. II-9

As we can see, the ordinary pendulum does not satisfy the mathematical condition (Figure II-8) but the one fixed to two points does (Figure II-9), therefore it is a stable system. Notice here that the only forces acting upon the body are gravity and suspender reactions.

Now let us apply the same principles to the airplane. An airplane is statically stable if a displacement from a given attitude of flight sets up forces and moments which will bring the airplane back to its original attitude. When we take the displacement angle as a function of time, we have the following properties (Figure II-10):

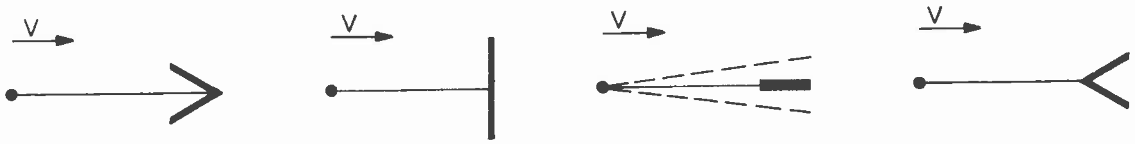


unstable (a) indifferent (b) oscillating (c) damped oscill. (d) stable (e)

Fig. II-10

The forces acting upon the airplane glider are gravity, lift and drag. The last two are created by the movement of the airplane and are called aerodynamic forces. Gravity and lift are opposite and equal in a steady flight condition, so they form a kind of a pendulum with one suspension point; therefore they create an oscillating system. In order to dampen the oscillations we use the forces on the controls. This way we obtain the "dampened oscillating stability" called "dynamic stability." See Figure II-10(d). However the forces on the controls are created by the forward speed; therefore they change in proportion to the second power of speed. But, because in an airplane the CG is forward of the center of lift, part of the forces on the controls are used to keep the airplane in equilibrium. This means they have to counteract the nose-down moment created by the CG and center of pressure positions. In the case of a conventional crosstail plane they are directed downward, loading the plane additionally. This is undesirable. What is worse is that the forces are a function of speed, so when the speed decreases, not only the "dynamic stability" decreases at the time when it is most needed such as landing or take-off, but also the plane loses its equilibrium and the nose dips. Let us see whether this can be avoided when we replace the oscillating system with a stable one. No longer needed is the damping action, and the plane would be stable at any speed.

In Figure II-11(a, b, c, d) we analyze the various configurations and find out what kind of stability they will produce in an airstream.



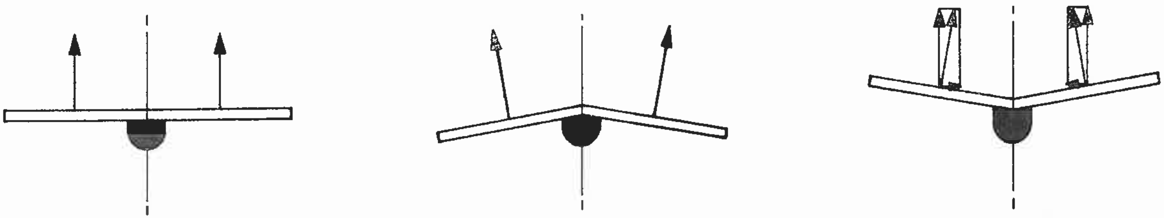
unstable (a) indifferent (b) oscillating (c) stable (d)

Fig. II-11

As we can see there is only one stable system (Figure II-11-d). The stability of an airplane is considered in roll (Figure II-12 a, b, c), yaw and pitch axes separately.

ROLL AXIS

The roll stability depends on the dihedral of the wing. In the case of a straight wing, the kind of stability we have selected remains constant. In the case of a sweptback wing the stable configuration changes with the angle of attack. At low angles and high speed the plane is stable. As the angle increases it becomes indifferent, and at high angles (landing and take-off) it becomes unstable. This characteristic is very undesirable. The solution would be a system which does not depend on the angle of attack. Figure II-13 would be such a solution.



indifferent (a) unstable (b) stable (c)

Fig. II-12

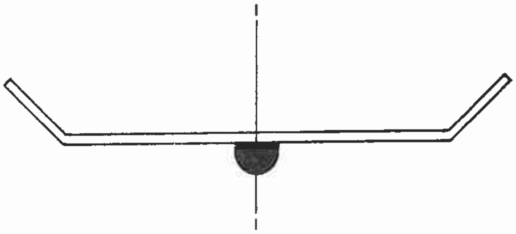


Fig. II-13

This stable configuration is based on an arrow or cone shape. It is used in the air refueling system and known as a "drogue" system. It is also used in space vehicles, which cannot use an oscillating damped system when returning from space and re-entering the atmosphere. It has also been used to steady the flight of arrows and bullets. The birds use it exclusively. Why do we not use it for the airplane is another mystery.

THE YAW AXIS

The vertical fin and rudder are supposed to assure a stable system in the yaw axis. As we have seen before, this is a system like a weather vane and results in oscillating stability. The only stabilizing factor is the pilot. When the planes grew bigger and the flight time became longer, the pilots started complaining about the continuous "kicking" of the rudder pedals, so the designers made a fix by installing an artificial "kicker" which they call a "yaw damper." They removed the symptom but did not cure the sickness. Adding more vertical surfaces to produce yaw stability will only increase drag and weight.

The better solution is the same slanted endplates on the wings, which assure a stable system in the roll axis independent of the angle of attack. These endplates should be toed-in about 4 degrees to obtain a stable system in the yaw axis. When a sweptback wing is used, the airstream on top of the wing is deflected outboard and the toed-in endplate will be parallel to the deflected airstream, producing only minimum drag, but the following benefits:

1. They prevent pressure equalization from the bottom to the top, which improves the effective aspect ratio, and consequently produce more lift.
2. Because they restrict the flow from the high pressure area on the bottom to the low pressure on the top of the wing, the so-called tip drag or "induced drag" is greatly decreased.
3. The tilted endplate toed-in at 4 degrees to the stream outside of the wing produces lift perpendicular to the surface, which at 30 degrees inclination has a vertical component of .5 of its total lift. When the inclination is 45 degrees, this added lift increases to .7 of the endplate lift. With all the beneficial effects, we do not pay any penalty, and gain a stable system in the yaw axis. In contrast, the vertical surfaces of a conventional plane give only oscillating stability and produce drag, torsional stresses on the fuselage, and interference drag in conjunction with the horizontal control surfaces.

PITCH STABILITY

The same reasoning, with which roll and yaw stability were discussed, applies to pitch stability. The system used in conventional airplanes is an oscillating system, and speed is needed to obtain "dynamic stability." The wing sections (airfoils) commonly used on aircrafts due to their positive Cm (moment coefficient) factor are the major source of pitch instability. There is a type of airfoil available with "intrinsic" pitch stability having a negative Cm. This is the reflexed airfoil commonly used on helicopters, which cannot rely on a crosstail for "dynamic stability." Why the reflexed airfoil has not been used commonly on fixed wing aircrafts is a mystery. The reflexed profile is suitable for both low and high speeds, has a larger laminar dwell, has a much better L/D ratio, and is stable. The birds use them exclusively.

Flying wing airplanes which use reflexed airfoils have adequate pitch stability without a tail. The stabilizing moment is provided by the total lift of the wing itself, which is many times greater than the down force on the tail of a crosstail airplane. Furthermore, an additional benefit from using a stable section is that the whole lift produced by the wing is used to carry the payload, while the down forces on a conventional stabilizer are loading the wing additionally, decreasing the payload, and producing torsional stresses. Thus the designer is forced to use higher lift sections, with correspondingly higher drag coefficients. While on the subject of drag, one should not overlook the high drag due to crosstail interference. The major drawback to conventional controls is that the down force on the horizontal stabilizer and elevator is only generated when the airplane is maintaining a forward speed. When the airplane's speed decreases below the stalling speed, it loses its stability and controllability.

Let us consider how the Bird Designer solved this problem. For pitch stability the bird uses a reflexed airfoil with a fixed center of pressure, sweepback and washout. The stabilizing force is the lift. This lift does not depend on forward speed. Even at a 90 degree angle of attack (vertical descent), lift is generated and is used to stabilize and control the bird. Should a gust raise the nose of the wing, lift increases at the tip, due to the washout. This moves the center of pressure outboard, resulting in a rearward displacement of the lift, due to the sweep back, causing the bird to nose down, thus restoring it to the initial position. In the case of a down gust the opposite takes place, causing a pitch up reaction.

SUMMARY OF THREE-AXIS STABILITY

The positive stability of Kasper Wing is a drogue type stability in all three axes.

1. Roll stability is achieved by inclining the tip plates outboard.
2. Yaw stability is obtained by the sweepback of the wings and by toe-in of the endplates. The rear part of each endplate is a rudder which moves outboard only. The directional stability can be increased by stepping slightly on both rudders simultaneously, thus increasing the toe-in.

3. Pitch stability is obtained by the center part of the wing having a positive angle of incidence; usually 4 degrees. The tip is provided with a horizontal triangular stabilizer which is inclined up, forming an airfoil at the tip with a negative angle of attack. Because the center section of the wing (±4 degrees) and both wingtip sections (0 degrees) form a cone pointing down they satisfy the requirement for drogue stability in the pitch axis. Additionally, at low speeds the elevons are moved up, increasing the angle between the center airfoil and the tips, creating a more pointed down cone. Therefore the pitch stability increases with decreasing speed, contrary to the "dynamic stability" which decreases with decreasing speed. The effect of this drogue pitch stability becomes a maximum at zero forward speed, which means in a vertical mush.

BALANCING THE AIRPLANE FOR THE CENTER OF GRAVITY MOVEMENT

Conventional Airplane

A shift of the center of gravity causes a change of the static margin moment and it has to be compensated for by the balancing moment of the force on the horizontal stabilizer. This limits the allowable CG movement to about 12% of the mean aerodynamic chord (MAC).

Flying Wings

Because of the lack of horizontal stabilizers Flying Wings are extremely sensitive to CG shift.

Canard

This design allows the greatest permissible movement of the CG in relation to the CP.

Bird

By moving the wings forward and back in the direction of the CG shift, the CP is always above the CG.

Kasper Wing

This wing is equipped with horizontal stabilizers at the wingtips. In the case of a shift of the CG, the stabilizer is moved up or down as in a conventional plane; however it not only creates a stabilizing moment but also shifts the center of lift in the same direction as the CG movement, keeping the "static margin" constant. This permitted a CG shift of 24% MAC on the BKB-1A glider, which is about twice as much as in a conventional plane.

III CONTROLLABILITY

PITCH CONTROL

Conventional Airplane

The change of pitch in a conventional airplane is done with the help of the horizontal stabilizer and elevator. They are horizontal surfaces, placed at a distance behind the wing, which produce forces up or down in order to create an up or down moment around the center of gravity. They work in the following way:

A down force on the elevator produces a nose-up moment, and an up force on the elevator produces a down movement of the nose. There is a drawback to this system which can be illustrated by the following example. Let us assume that we are carrying a heavy beam balanced on our shoulder and we want to lift the forward part higher. Here comes a well meaning helper who hangs himself on the rear end of the beam. When we are already loaded to the limit, we cannot stand the additional load and we collapse. Would it not be much more logical if the helper would lift the front part? There is an additional disadvantage when the controls are located aft of the wing. The fuselage is in the most turbulent zone and the turbulence increases with increasing angle of attack, which happens during landing and take-off. This means, in the previous example, the helper, who has to assist, is standing in the roughest place, covered with slippery stones and mud. How does this strike you? But this is not all . . . The horizontal stabilizer is producing a down force all the time to keep the airplane level, and this down force has to be supported by the wing in addition to the weight of the supporting structure: like our helper pulling the rear of our beam down. But perhaps there are other advantages of this apparently illogical arrangement. The crosstail shape is producing quite a high drag due to interference even when the rudder or the elevator are neutral. We know that parachutes, used to slow down the high landing speed of fighter planes, have the form of a cross and we learned from experience that the cross will produce even a higher drag than a full parachute. For all practical purposes the plane is dragging this cross-parachute behind it all the time and paying for it.

When we actuate the elevators, they produce the forces needed to change the pitch attitude of the plane. The secondary effects of the elevator deflection are:

The forces acting on the centerline of the airplane increase the loading of the wing. In the case of pull out, when we need maximum lift, they are loading the aircraft additionally and in the worst location, the center, producing an increase of the bending moment of the wing. At the same time, the stabilizer is preventing the plane from rotating, thereby producing a high torsional moment in the wings. Those forces are transmitted to the wing through the fuselage which causes a bending moment in the latter. As a result the wing and the fuselage have to be built stronger which means more weight. This is the price for the primary function of the elevator.

The forces generated on the horizontal control surfaces are aerodynamic forces, which means they are generated by the forward speed of the airplane. Because the minimum force required to balance the plane can be computed, the minimum speed which can generate this force is also known. It is known by the name "minimum control speed." This means that below this speed the airplane is not controllable. As discussed in the previous chapter "Stability," it loses its inherent stability also. The only thing that can save the airplane is sufficient altitude which will permit sufficient gain of speed to its critical "minimum control speed." However, because the plane at take-off and landing is flying at the low speeds where the margin between the minimum control speed and no control at all is the least, most of the time we do not have sufficient altitude to regain the necessary speed.

The Earlier Flying Wings (Tailless Airplanes)

The elevators were flaps located at the trailing edge on the centerline of the plane. They worked on the same aerodynamic principle as on the conventional plane, but were somewhat more effective. Their action was limited by the minimum control speed, but when not actuated they were not causing additional drag. They did load the airplane when actuated by increasing the bending of the wing, but did not cause torsion. They also did not stress the fuselage, but the drawback of their dependence on speed still remained.

Sweptback Flying Wings

Most often both the existing and the earlier Flying Wings had to have sweepback in order to obtain a minimum of directional stability.

In such a case the placement of the elevators, either inboard or outboard, produces a significant secondary effect. Because they are an integral part of the wing section, they change the profile when actuated. When they move up, the wing section is transformed into a reflex airfoil and the lift decreases over the part of the wing covered by the elevators. This causes a change in the lift distribution. The same occurs when the elevators are moved down, the camber of the profile increases causing increase in lift. Due to the sweepback the center of lift moves forward or aft, in relation to the center of gravity. This causes a nose-up or nose-down moment. Whether the moment caused by the shifting of lift is added or subtracted from the aerodynamic moment of the elevators depends upon the spanwise location of the latter. When the elevators are located inboard, the "lift shift" moment is subtracted from the elevator aerodynamic moment. When they are outboard, at the wingtips, the moments are added which is beneficial for two reasons:

1. It makes pitching moment control more sensitive and, more importantly, because the lift is not a function of the forward speed, even the wing drag of a plane mushing vertically down may be used to control the pitch. However, when we examine the sweptback wings which have been built up to now, every one has had the elevators on the centerline of the fuselage, and none have had them at the wingtips. There must be a reason why the designers chose this location instead of the more advantageous one. There is a very good reason for the inferior location. In order to control the plane in roll we need ailerons, and they have to be placed at the wingtips. It so happens that the ailerons also produce a detrimental effect which is adverse yaw. In conventional airplanes this adverse yaw is counteracted by the rudder, but in the case of flying wings yaw is so pronounced that it endangers the safety of the plane. The plane, instead of rolling in the direction desired by the aileron movement, yaws in the opposite direction, increasing the differential movement of the aileron, and still does not eliminate this adverse yaw. For conventional airplanes this adverse yaw is acceptable due to the availability of the rudder, but in the case of flying wings a more radical action

has to be taken. The ailerons have to be redesigned in such a way that the roll action is maintained but the adverse yaw is completely eliminated. The solution which was finally accepted was the use of split flaps or spoilers, which are actuated only on the down moving wing. This is an acceptable solution to adverse yaw, but a spoiler or a split flap cannot be used as an elevator and it occupies the place on the wingtip where the elevon should be located.

2. When the elevator is moved to the centerline, the effective pitching force is the difference between the aerodynamic force on the elevator and the opposite forces caused by the lift which is shifted outboard due to sweepback. So long as the elevator force is predominant the plane follows the movement of the controls. When the angle of attack increases, the lift increases and the elevator forces decrease. At the stall, or close to it, the moment due to the "lift shift" becomes prevalent and the wing reverses its direction of movement and instead of nosing up the plane goes into a vertical dive. This phenomenon is known by the name of "control reversal" at high angle of attack. Control reversal is a second limit to low speed. The first is still "minimum control speed."

The earlier flying wings also show a very dangerous property: TUMBLING. In itself tumbling would not be so bad if it could be stopped, but this has proven to be impossible. Every flying wing which has tumbled has ended in a crash with the pilot killed. The author has made a thorough study of the causes and prevention of tumbling. When a wing is tumbling two moments are acting upon it.

1. The inertial moment in the direction of tumbling.
2. The aerodynamic damping moment in the opposite direction. When the aerodynamic damping moment is greater than the inertial moment, tumbling cannot occur. When both are equal a tumble at a constant RPM can occur. When the inertial moment is larger, then tumbling will occur and increase in RPM until the aerodynamic damping moment equals the inertial moment. But because the inertial moment is constant and since with a constant tumbling RPM the aerodynamic damping moment cannot be changed (the plane being in a stalled condition where the controls are not working), a steady state develops. This is stated in the engineering textbooks as the reason why no flying wing ever recovered from tumbling.

Canard Airplanes

In the last few years designers' interest in the canard design has increased considerably due to some beneficial properties it possesses. Historically, the Wright Brothers' airplane, with which the first successful flight was made, was a biplane canard. Due to several reasons this configuration was later changed to the aft conventional tail. The first main reason was that difficulties arose from the use of a single engine and a single propeller by the contemporary airplanes and secondly, the application of the airplane to warfare. The military required very maneuverable airplanes, capable of inverted flight for which the canard configuration was not especially suitable. The experiences during the first World War influenced the direction of the postwar development of aeronautics.

In connection with this latest development some peculiar properties of the canard system, which makes it so different from the conventional system, were overlooked, and very few aerodynamic studies were ever made thereafter as compared to the conventional system where the control surfaces are placed behind the main wing.

The canard system has the basic advantage that the horizontal control surfaces take part in the lifting of the load, while in the conventional system they are basically used to balance and to control the plane. By increasing the angle of attack, the lifting force of the canard is increased and is added to the lifting force of the main wing. While in the conventional system, the force on the horizontal control surfaces becomes negative and must be subtracted from the lifting force produced by the main wing. In the canard configuration this amounts to about a 20% increase of the lifting force, while at the same time the induced drag of the control surfaces is increasing. The canard configuration is therefore offering the designer, without penalty, and nearly without a weight increase, an additional lifting surface, which decreases the wing loading, shortens the take-off and landing distances, and increases the rate of climb.

But there are also disadvantages in addition to the already mentioned poor maneuverability and lack of capability for inverted flight. In the canard configuration, where the elevator surfaces are located ahead of the main wing, the air flow deflected by them changes the flow on the main wing to a great degree. The vortex sheet forming at the trailing edge of the canard surfaces is not yet fully developed when it reaches the main wing, and the horseshoe vortex is not yet fully formed. This makes it very difficult to establish the speed of the airstream and its angle of flow just before it reaches the main wing, which is needed to establish the necessary wash-in of the portion of the main wing required to maintain an even lift distribution on the wing. Additionally, because the flow is deflected by the canard we have to determine a particular angle of attack for the wing. Flying at any other angle of attack we are not getting the optimum performance. The additional drag which the canard surfaces are producing, even in neutral position, will still be present.

The Bird

The bird has the ideal system. He has no elevators or rudders. As we discussed in Chapter II "Stability," the bird uses the drogue system. The forces used by this system are gravity and lift. They will always align in the vertical direction. When the lift moves ahead of the CG, the nose rises to align with the CG in the vertical plane. For slow speed (high angle of attack) the bird moves the wings forward and for high speed (low angle of attack) he moves them back. Because the two forces, gravity and lift, which the bird utilizes in order to change the angle of attack, are independent of the flying speed, he has full pitch control at any speed, from high speed down to zero speed. This way the "minimum control speed" is eliminated and a maximum of safety is achieved. Birds seldom stall.

The Kasper Flying Wing

When I contemplated how to design an airplane which would be as close to the bird's design as possible, I realized that it would be impossible to imitate the bird's mechanism consisting of a back and forth movable wing, which also can be twisted at will. So the only solution was to try to obtain the same or at least a similar aerodynamic effect by using different mechanisms. As far as pitch control was concerned, knowing that the bird is shifting his center of lift by moving the wings forward or back, the crucial feature was to be able to move the center of lift without moving the wings. This was achieved with the following design. The wings are swept back. The airfoil has to have a center of pressure which will not move with a change in the angle of attack, so a reflex profile was selected. Elevons are located at the wingtips and the wing has to be of a rectangular planform, because lift is mostly needed at the elevons.

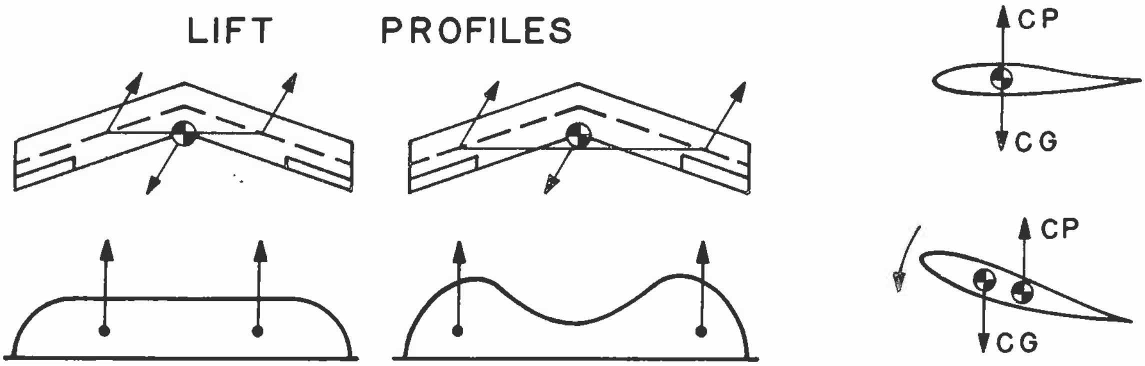


Figure III-1 illustrates the system.

When the elevons are moved up, the profile changes to high reflex with loss of lift near the wingtips. This changes the lift distribution from nearly rectangular to triangular. The center of pressure of the wing shifts inboard and forward due to the sweep. In addition, up elevons produce a nose-up movement of the airplane, due to the aerodynamic forces, similar to the conventional elevator. A third force, acting in the same direction, is due to the change in the drogue stability configuration resulting from the increase in the washout angle at the wingtip. The airplane will assume a higher angle of attack where the drogue stability is again achieved. Thus we have three independent systems acting in unison to produce the increase in the angle of attack. The nose-up moment, due to the down force on the up elevators, is a function of speed, same as the control forces on the elevator of a conventional plane, but the shift in the center of lift and the resulting nose-up moment is independent of forward speed. The new drogue stability arrangement is also independent of forward speed. Therefore two out of three forces are creating a nose-up moment independent of the forward speed of the airplane.

The only problem which remains is the adverse yaw. There are two possibilities. The first is to use a different type of control surface for roll. The second is to increase the drag on the up aileron and decrease it on the down aileron. Both solutions were employed. I knew from experience as a pilot that the slowest response in any aircraft is in the roll axis. Having two systems increases the roll response and in addition it is an added safety factor in the case of a partial failure of the controls. Adverse yaw is eliminated in the following manner: A special trim tab or flap is hinged to the trailing edge of each aileron. The connecting arm between the wing and the flap (see Figure III-2) is positioned to always move the flap up when the aileron is deflected. The tab remains neutral when the aileron is neutral.

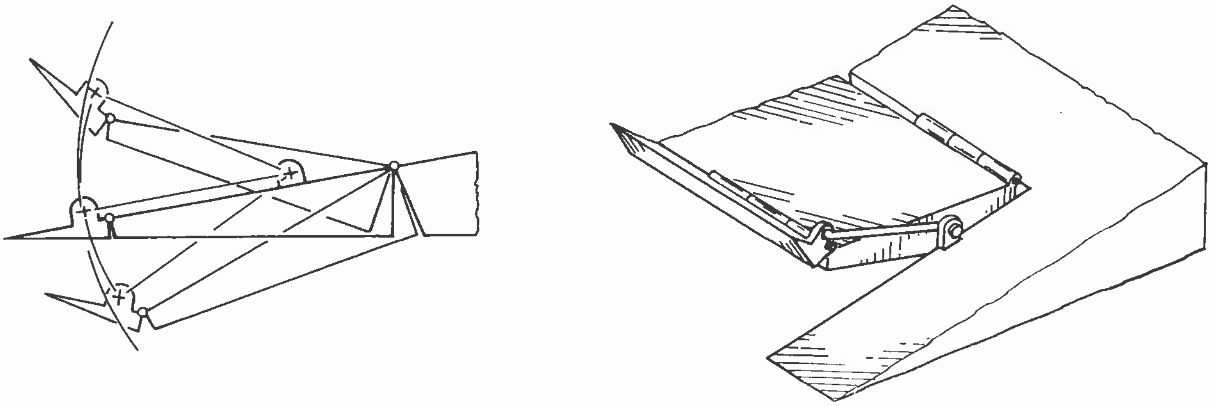


Fig. III-2

The ailerons have a 1:5 differential in the up and down movement. This peculiar flap has an additional beneficial effect. When the elevons are used as elevators, the sensitivity of the up movement is increased and the sensitivity of the down movement is decreased which equalizes the sensitivity in pitch at high and low speeds, a very pleasant quality from the pilot's point of view.

Additional Benefits

1. Location of the elevators at the wingtip produces a beneficial effect when they are actuated upward. The aerodynamic force which is directed downward is changing the load system from cantilever to a tip supported configuration, which reduces the maximum bending moment to approximately 1/3 of cantilever moment on pull up.
2. With the upward deflection of elevons the lift distribution over the wing changes from practically rectangular or elliptical to a triangular one. This effect is achieved in conventional airplanes by using a tapered wing to reduce the bending moment.
3. Because the down force, in the case of pull out, is not concentrated at the wing tip but is uniformly distributed along the length of the elevon, the bending arm of the lift is reduced which means that the wingspan subject to bending is now reduced, resulting in an additional reduction of bending moment.

To illustrate the dramatic reduction in stresses, consider the case of the BKB-1A glider. The maximum bending moment for a cantilever wing would be reduced from $Mb_{max} = \frac{Wl}{4}$ to approximately $\frac{Wl}{11}$ where W is the total load over the the wingspan and l is the half span of the wing. This means that an aircraft built to withstand 5.62 G (the gust load) is capable of taking a load of 9.13 G in maneuvering, which is more than a human being can take. It means that the Kasper Wing has to be stressed only to 5.67 G to be fully acrobatic.

4. By being able to use a rectangular wing with endplates, which increases the effective aspect ratio by about 25% the wing efficiency also increases from about 70% for a tapered wing to nearly 120%. This means that a wing can be made shorter and lighter (stressed to 5.62 G for bending only) which results in higher payload and less drag.
5. Location of the elevon near the wingtip's trailing edge results in a variable washout, which increases with increasing angle of attack. For cruise configuration the washout can be set at zero so no additional drag is produced at high speeds, in contrast with built-in geometric washout. This is ideal because the desired washout is attainable when needed.
6. The absence of the stabilizer and elevator on a long arm at the centerline of the airplane eliminates torsion of the wing on pull out. It also eliminates all aerodynamic stresses on the fuselage, permitting much lighter construction.
7. The elevons, being part of the wing profile when not used for maneuvering, are not producing any additional drag as do crosstail surfaces.
8. The uni-directional tab on the elevons, provided to eliminate adverse yaw, makes the elevons more effective at high angles of attack (low speeds) which from the pilot's point of view is very desirable. With proper dimensioning of the tab, the plane can have the same sensitivity at all speeds.
9. A very important obstacle which slowed down the development of a safe flying wing, straight or sweptback, was that they all suffered from a very unstable behavior, namely "tumbling," which usually ended in a crash. There was no way to recover from tumbling. In fact no tailless plane which went into tumbling ever recovered from this maneuver and no pilot escaped alive. Very little data exists about tumbling. Up to now it was believed that tumbling cannot be stopped once it starts. Therefore, all the efforts of flying wing designers went into designing a wing immune to tumbling. This was not always successful. Several German flying wings tumbled and crashed, killing the pilots.

Since I am the only pilot who has deliberately tumbled a wing and recovered, I feel that it is my duty to share this experience with my fellow pilots and aerodynamicists.

First: what is tumbling?

Tumbling is a continuous rotation of a wing around the spanwise axis. It can be compared to the spinning motion of a tail-equipped plane. It takes place at the stalling angle. After tumbling is established it continues at a constant turning rate and a steady rate of descent. With the early conventional airplanes, recovery from a spin was by trial and error. Later it was learned that when the CG was in a forward position, so that the plane was spinning in a nose down attitude, and the tail surfaces were moving in a downward spiral, sufficient forces were generated on the elevator and rudder to transform the spin into a dive from which the recovery was known. When the DG was too far aft, the spin became a "flat" spin from which there was no known recovery.

Fortunately the spin could be tested in a vertical wind tunnel; thus the risk to the pilots was greatly reduced and scientific research was possible. The end result was the understanding of spins, and methods of recovery from them were fully mastered. The maneuver became useful for losing altitude safely in cases of emergency, without overstressing the airplane. Spinning also proved useful as an escape maneuver in aerial combat.

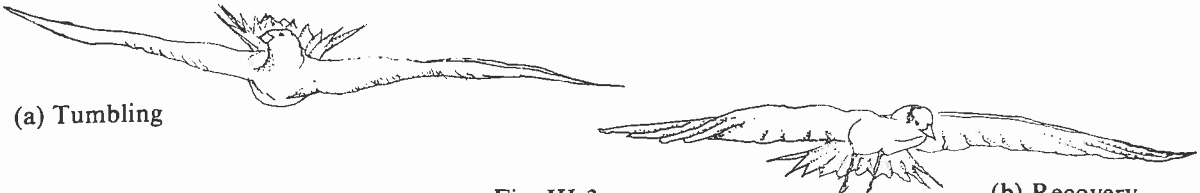
Tumbling is also a steady rotary motion, but around the spanwise axis. As long as no additional forces are added, it is a steady state which can neither be accelerated nor decelerated and stopped.

The general equation for tumbling is:

$$M_I \underset{\leqq}{\geqq} M_{AD}$$

Where M_I is the INERTIAL MOMENT of the airplane around the pitch axis, and M_{AD} is the Aerodynamic damping moment generated by the tumbling motion of the wing. When M_I is smaller than M_{AD} no tumbling can occur. When M_I is equal to M_{AD} a steady tumbling occurs and when M_I is greater than M_{AD} an accelerated tumbling results. When M_{AD}, which increases with revolution rate, becomes equal to the constant M_I, the tumbling continues at a higher rate of rotation. Because M_I remains constant during tumbling and M_{AD} now is also constant, we have reached a steady state, which means that the rotation cannot be stopped. This was true with earlier flying wings.

In spite of the apparently logical formula for tumbling, the tumbling pigeons and mockingbirds tumble for fun and recover at will. Observing these birds, I noticed that they change their configuration to recover from tumbling. They tumble with their tail up, nearly perpendicular to the wing, and recover by straightening and lowering their tail (Figure III-3).


(a) Tumbling

(b) Recovery

Fig. III-3

These birds can reverse the direction of their AERODYNAMIC DAMPING MOMENT with their tail, adding to or subtracting from the INERTIAL MOMENT.

Another phenomenon noticed was that the birds always tumble backwards. This observation of the tumbling birds led to the discovery of the maneuver which stops the tumbling motion of a flying wing.

As before, unable to match the flexibility of the bird mechanism, I decided to obtain the same aerodynamic effects by different means. A moderate sweepback and the controls at the wingtips proved to be the right answer. With this configuration it is possible to induce and stop the tumbling motion, also to reverse the tumbling from backwards to forward.

The reasoning for control effectiveness is as follows: Tumbling occurs around the center of gravity. When rotating, due to the sweptback wings, the wings are describing two cones with the apex at the CG. Therefore the wingtips are moving in a circle with sufficient speed to make the tip elevator effective. To introduce a backward tumble, we pull the elevator up, adding the moment of the aerodynamic force to the inertial moment, until the damping moment is equal to the inertial moment. When we want to stop tumbling we push the stick forward. The force on the elevator is now reversed, producing a moment opposite to the inertial moment, and the tumbling stops. For additional control, stepping on both rudders moves them perpendicular to the motion of the wing, increasing the damping moment, which also helps to stop the tumbling. This does not mean that the basic equation for tumbling is wrong. In the case of the sweptback wing with controls at the tips, two additional factors are added or subtracted from the left side of the equation. The equation for the Kasper Wing will be:

$$M_{I} \gtreqqless M_{AD} \pm M_{ELEV.} - M_{RUDDER}$$

In this way the tumbling equation ceases to be a steady state. In earlier flying wings the moment of the elevator was equal to zero. Rudder moment was also zero. The necessary configuration for flying wings to control tumbling is:

1. Sweptback wings.
2. Elevators at the tips.
3. Rudders at the tips, both movable independently outward.

With BKB-1A glider configuration above I tried the first backward tumble at 5000 feet. The last one was at 200 feet altitude and consisted of three tumbles, alternately backward and forward, and half a tumble backward with still 50 feet to spare.

The proper execution of the tumbling maneuver and the follow-up recovery is accomplished as follows: Half-loop the wing until it is on its back, then push the stick slowly forward to bring the wing to a full inverted stall. The stick should be all the way forward to the stop. As soon as the wing starts to fall off, pull the stick sharply back to the stop. As long as you keep it there the wing keeps on tumbling. Releasing the stick and pushing it forward stops the tumbling. For the first attempt it is advisable to release the stick after half a turn, until you get used to this quite unusual maneuver.

On my first attempt the BKB-1A was tumbling at a rate of 60 RPM. This means one full tumble per second. At this rate the measured acceleration, one foot above the CG, was 2 G's. The orientation of the pilot was not impaired. It was possible to stop tumbling at the desired attitude, preferably straight and level. As soon as the horizon started to come up, I released the stick gently, to meet the horizon with a slight back pressure on the stick. After mastering the art of tumbling, the first interesting question was to find out what was influencing the rate of tumble. According to the formula, an increase in the inertial moment should cause a higher rate of tumbling. In order to increase the inertia around the transverse axis, without shifting the CG too much forward, I placed 10 lbs. of lead in the nose of the glider. This is advantageous because the shift of CG occurs linearly with the distance from the neutral axis, while the inertia is increasing with the square of the distance. On the first attempt to tumble with the added weight, I was caught by surprise. After pulling the stick back, in the inverted position I heard a loud crack. I did not dare to move the controls. The world was revolving around and around. I could not get a fix on the horizon. The only things I could see were flashes of dark and light. The top priority was to discover what caused the loud crack, and whether the wings had suffered any damage. I looked at the right wing. It was still there in one piece. Then to the left; no damage. While looking at the wings it seemed to me that the plane was flying normally. Only the world was swirling around.

I found that the best way to avoid vertigo was to fix my eyes on the wing. The next check was the instruments. Altimeter, 4800 feet so only 200 feet were lost up to now. G-meter — 4 G, a little more than I anticipated; airspeed, zero; rate of climb, minus 3000 ft/min. Then I noticed that I was a little more slouched than usual and that the belts were loose. I moved, and I heard a cracking in the back. Now I knew. The seat back-plate, which was slightly cracked before, had broken and bent and this caused the loud noise. No wonder, supporting 4 G's. Now I tried to catch the moment when the plane would be level with the horizon. It was impossible; the rotation was too fast. So the only thing remaining was to push the stick slowly forward. The tumbling stopped, but I found myself in a 45° dive. Leveling off was an anticlimax. I took a deep breath, perhaps the first since the tumbling started. I still had 3800 feet of altitude left. I tightened the belts, set the G-meter to zero, reset the stop watch. Increased the speed to 70 mph. Stick slowly back with a continuous motion. The plane turned on its back, now stick slowly forward, the nose lifted, there was an audible gasp as the noise from the wind ceased, now the stick full back, the tumbling started. I pressed the stopwatch counting the revolutions. At the count of 10 I stopped the watch. The wing continued tumbling. I noticed that the G-load on my body acted strangely. I was not so much pushed down; rather I was stretched out and felt a strong pull on my legs. A quick glance at the altimeter showed 3000 ft.—time to stop tumbling. Not being able to get a fix on the horizon I selected the moment when the "black" appeared and eased on the stick. Great!! The horizon was just level. The remainder of the flight was anticlimactic. I checked the stopwatch — 5 seconds, 10 tumbles calculates to 120 RPM, G-meter registered 4 G's; generally unpleasant and difficult to pull out to a level attitude. So long as one has sufficient altitude this maneuver is safe, but no good for air shows because it is too high. The public will not be able to see what I am doing. After landing, the 10 lb. lead weight was removed. Calculation showed that, with the 3000 ft./min. sinking speed, the speed of the descent was slowed down to 34 mph, which is quite reasonable.

At the subsequent air shows I practiced to tumble at 60 RPM & 2 G's until I became so proficient that I could use it instead of the final turn before landing. I flew downwind inverted above the runway, arriving at the end with 200 to 300 feet altitude, then made ½ or 1½ tumbles, depending upon the altitude, and landed into the wind. This pleased the crowd. It was another "first."

Subsequently I became interested in the possibility of tumbling forward. I knew that the wing had to be stalled and the whole range of movement of the stick needed to be available. In order to tumble forward, the stick movement has to be from back to forward. I did not like the idea of starting the movement nose down, so the only alternative which remained was to tumble the wing first backward, stop the tumble in the inverted position and then push forward. On my next flight this was tried. I made a back tumble and after a full rotation, being inverted with the stick fully back, I pushed hard forward. The nose lifted, swung over and continued tumbling forward. The recovery was as easy as the backward tumble. The maneuver was accomplished at 60 RPM and twice gravity. The only difference was that the tumbling stopped inverted, so it required another half tumble backwards to be in the normal flight attitude.

Tumbling became standard at subsequent air shows. By this time (1970) the FAA removed the altitude restrictions from the aerobatic license for the flying wing after I demonstrated the following maneuver:

I speeded up to 80 mph, diving to the ground, touched the grass on pull up, climbed to about 300 feet, half looped, tumbled full back, reversed forward full tumble, half tumble back, stopped and landed at the spot where I first touched at high speed.

This ends the story of tumbling, a maneuver which had never been done before. It even beat the tumbling pigeon which can only tumble backwards. It was most reassuring that I never had to use the emergency maneuver of pushing both rudders out to stop tumbling.

The only reason the wing for the BKB-1A could stop tumbling was due to the sweepback of 13° and the elevator location at the tips, which were rotating at 60 RPM. The rotation resulted in an airspeed of about 40 mph across the controls which therefore remained fully effective.

The tumbling study explained another puzzle: All cases of an aircraft which tumbled and did not recover happened at the end of the stability test program. In order to obtain an adequate stability the CG of those wings was moved forward. This was done by weighting the nose of the fuselage, which increased the inertial moment until it became greater than the damping moment. When the stability was tested at close to the stalling speed, as is usually done, and the pilot pulled up, the wing began to tumble. The pilots were subjected to the unusual "stretching" acceleration and, due to the simultaneous high RPM's, lost their orientation and did not jump out. This is my explanation based on the experiences I have had with the fast (120 RPM) tumbling rate

ROLL CONTROL

Conventional Plane

The roll control is accomplished with the aid of ailerons. These are flaps, usually located at the wingtips, which move in opposite directions when actuated by the movement of the stick or control column. Their action is as follows: moving the stick to the right, the right aileron moves up and the left one moves down. The up aileron creates two forces:

1. Aerodynamic force directed downward.
2. By changing the profile to a high reflex, it spoils the lift on the wing.

The down aileron changes the camber of the profile, increasing the lift coefficient. This causes an up force.

The combination of the two forces, down on one wing and up on the other wing, will roll the aircraft. However, besides the desirable effect, some undesirable forces are generated. The down aileron causes a much greater drag force than that caused by the up aileron, which is in partially separated flow on the top of the wing. This higher drag is acting in the opposite direction from the roll. It is called "adverse yaw." In order to decrease this adverse yaw, several means have been used:

1. Differential aileron movement. The down aileron moves only a fraction of the up aileron movement. The most commonly used differential is 1:5. This "fix" is helpful, but it reduces the amount of lift increase on the down aileron. Consequently the effectiveness of the aileron decreases.
2. Another "fix" used before the World War, was the so-called Freeze aileron which increased the drag on the up aileron. See Figure III-4.

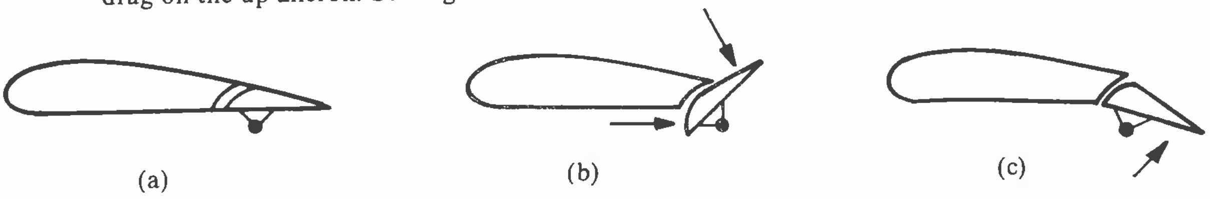


Fig. III-4

The Freeze aileron is hinged aft and below its leading edge, thus the nose of the up aileron is protruding below the wing profile, causing an additional drag which balances out the down aileron drag. This solution permits a decrease of the differential movement making the roll more effective.

3. For aircraft which have a longer wingspan and higher wing loading, where the rate of roll is too slow, spoilers can be used on the down moving wing. If the spoilers are placed ahead of the ailerons they decrease aileron efficiency and what is more important, once they are used as ailerons they can not be opened on both wings at the same time to act as spoilers or airbrakes.
4. Another design used to obtain a rolling movement, without creating adverse yaw, was the split flap. See Figure III-5.

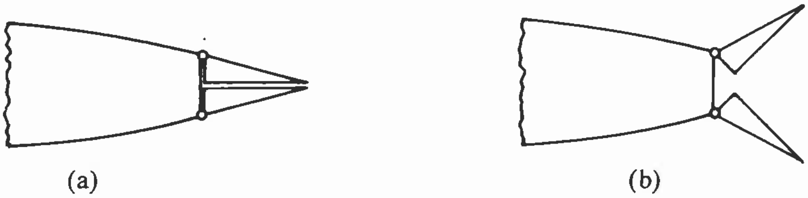

(a) (b)

Fig. III-5

The upper part of the split flap causes the roll moment and the lower part of the flap causes the yaw moment in the roll direction. The roll moment of the upper flap is decreased by the opposite roll moment of the lower part of the flap.

The most detrimental aspect of these devices, designed to produce roll without adverse yaw, is the fact that when we use either Freeze ailerons, spoilers or split flaps, none of these control surfaces can be used as elevators. Because these devices must be located at the wingtips, the elevators have to be shifted toward the center of the wing. This creates very detrimental secondary and tertiary effects, which have already been explained in the "Pitch Control" section.

On conventional planes with a tail, the residual "adverse yaw" is overcome by using the rudder in conjunction with the aileron in a movement called the "coordinated turn." This will keep the ball, in the turn and bank indicator, in the center position. This requires some skill from the pilot.

Canard Configuration

With the canard configuration the adverse yaw is especially troublesome because it cannot be dampened by the ineffective rudder. At low speeds and high angles of attack the ship can turn in the opposite direction to the intended roll. Therefore the use of spoilers or split flaps becomes mandatory in spite of their detrimental side effects. This accounts for the very limited maneuverability of canards. Wide turns with bank angles not exceeding 30° are standard for the canards built to date.

Flying Wings (Tailless Airplanes)
Unswept Wings

Similar to the canard configuration, the designer of the unswept flying wing is forced to replace the tip ailerons with spoilers or split flaps in order to avoid adverse yaw. Consequently the elevators have to be placed at the center of the wing, which on a straight wing does not make much difference except that due to a shorter moment arm in relation to the center of gravity their efficiency is low. The balancing moment decreases when the elevators are in the zone of separated flow at high angles of attack. At the same time, when the elevators are in the up position for low speed the geometric washout is opposite to the one required for high angle of attack. All of this spells roll instability.

Swept Back Wings

As already discussed for Pitch Control for sweptback wings, having the elevators in the center of the wing leads to detrimental effects. Pitching moment, being the difference between the elevator moment and the lift-shift moment, has low response and at high angles of attack, pitch control reversal and uncontrolled tumbling can occur. The elevators being in the stalled zone of the wing and the usually wrong geometric washout aggravates the lack of control.

The Bird

In order to roll, the bird twists his wingtip to a high washout. When the roll rate has to be very fast, the inner wing is folded partially while the outer wing remains in the normally extended position. For a slow roll at low speed, the tail is twisted opposite to the roll direction. See Figure III-6.

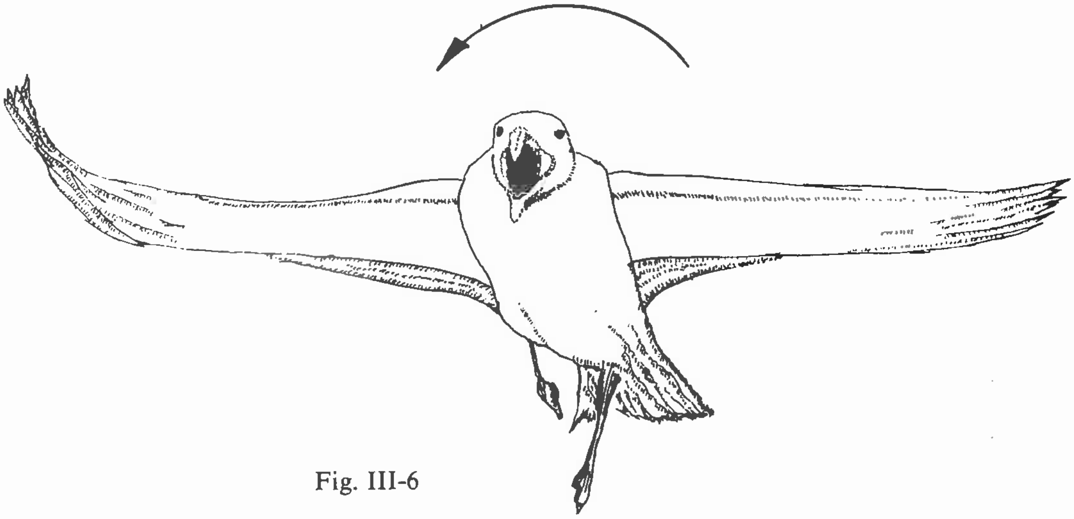


Fig. III-6

The Kasper Wing

The roll control for the Kasper Wing consists of two independent systems which can be used alternately or simultaneously for a very fast roll rate. The first system consists of the two standard ailerons with a differential ratio for the up and down movement. A very important addition, which is the primary means of eliminating the unwanted adverse yaw, is the installation of the "anti-yaw" tab. This is a tab, located at the outboard trailing edge of the aileron, with the unique property of only moving up, whether the elevon moves up or down (Figure III-7). On the Kasper Wing the ailerons also act as elevators through the use of a "mixer" mechanism. Hence they are referred to as "ELEVONS."

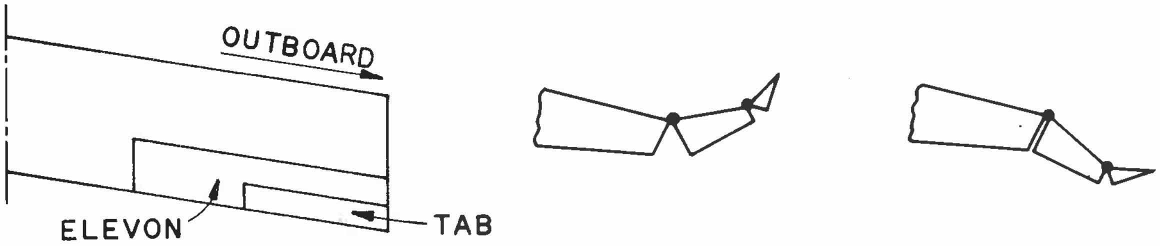


Fig. III-7

When the elevon moves up, the tab also moves up increasing the drag of the up elevon. On the opposite down moving elevon, the up moving tab decreases the drag. With proper dimensioning of the tab, the drag of the up elevon can be made greater than the drag of the down elevon. The result is desirable yaw in the direction of the roll.

The wingtip rudders are the second roll control system which also have the dual function of yaw control. In order to balance out the aerodynamic force on the deflected rudder, an aerodynamic balance, forward of the hinge line, is provided (Figure III-8).

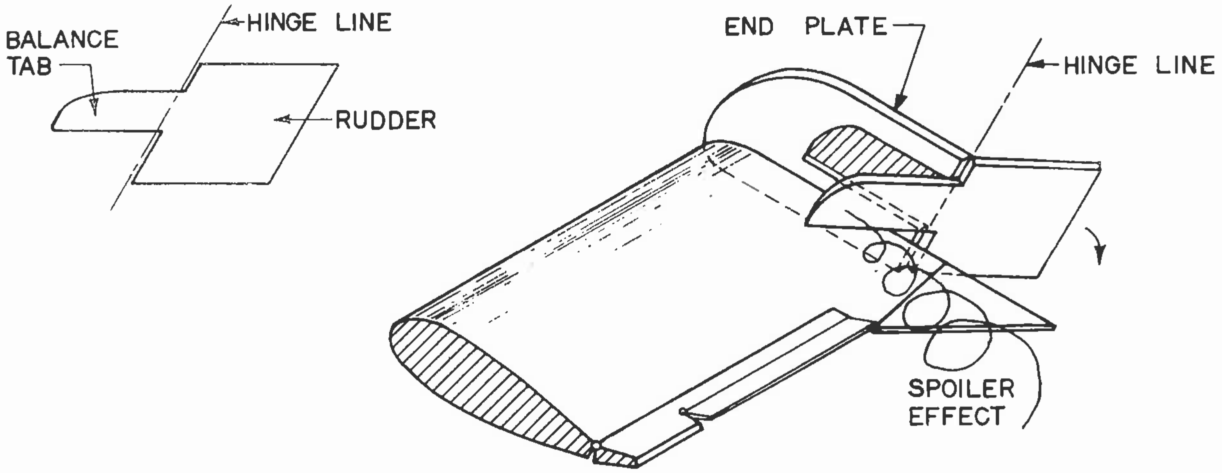


Fig. III-8

This aerodynamic balance moves over the wingtip when the rudder is deflected, acting as a spoiler on the wingtip and also adding to the drag. The spoiler action decreases the lift of the wing. Consequently the lift differential on the wing produces a rolling moment in the direction of the actuated rudder. Additionally, because the endplates and rudders are inclined outboard, when the rudder is actuated, its inclination produces an additional downward force helping the roll. Actually the turn can be made with the rudder alone, without the need of aileron to "coordinate" it.

YAW CONTROL

The Conventional Airplane

The directional or yaw control on conventional airplanes consists basically of a longtail with a vertical surface at the rear end, split into a fixed vertical stabilizer or fin and a movable rudder. This basic arrangement does not seem to be very logical. This can be illustrated by the following example:

> Let us assume that we have a long table which has to be turned around. We can nail a long 2 x 4 to the center of the table, grab the end of it and turn the table. Or we can grasp one end of the table, representing a wingtip, and swing the table around which is naturally much more logical.
>
> The conventional method is not the only illogical system. There are more.

1. The vertical surfaces, forming a cross with the horizontal stabilizer and elevator, generate the greatest possible interference drag — much greater than the sum of the drag of those surfaces by themselves. In order to get an idea about the magnitude of this interference drag, we only have to recall that when we used braking parachutes on some fast landing military planes, it was found that a "cross parachute" produced even more drag than a full one.
2. Horizontal control surfaces are commonly placed below the rudder. In a spin they screen the rudder which often makes the recovery very difficult. In some aircraft "spin recovery" parachutes have had to be added.
3. The aerodynamic center of the deflected rudder being outside of the neutral axis of the fuselage produces a torsional moment requiring a stronger, and therefore heavier, construction of the fuselage.
4. When applied alone, the rudder at the end of the tail will not cause a coordinated turn. A coordinated turn (with the ball in the center) requires the simultaneous use of the aileron and the rudder. The proper proportion of each control varies from one airplane type to another. It is necessary to familiarize pilots with each new type of airplane. I compare this to a need to learn writing anew every time we use a different pen.

5. Another somewhat troublesome effect, caused by the vertical stabilizer and rudder location on conventional airplanes, takes place when the control surfaces are located above the neutral axis of the fuselage. When the rudder is actuated, the force component perpendicular to the fuselage axis causes not only torsional stresses but also a rolling moment opposite to the desired yaw moment. I would call it "adverse roll." This adverse roll moment further complicates the execution of a perfect "coordinated turn." This is recognized by aerobatic pilots as the most difficult aerobatic maneuver. It can prevent recovering from a spin with rudder alone.

Flying Wings

Most of the earlier flying wings did not use rudders (Lippisch, Horten, and others). The turn was executed by banking (rolling) in the desired direction. This limited control ability resulted in large radius turns with banks limited to approximately 30°. In addition the execution of a side slip was impossible. This was especially objectionable at low speeds on crosswind take-offs or landings, where this lack of directional control caused the most crashes. This malady was well known to the wing designer. I quote from the report made by John K. Northrop before the Royal Aeronautical Society, London, England on May 29, 1947, "Rudders for all wing aircrafts are the chief difficulty. Unless large fins are used a conventional rudder cannot be employed. If large fins and rudders are used, an objectional adverse side force due to the rudder is inherent, since the rudder moment arm is small and the side force comparatively great."

"The use of pure drag rudders is feasible on the all-wing type because it is not necessary from a performance standpoint to fly at zero yaw. Thus in the case of an engine failure, equilibrium condition involving a yaw angle and the resultant corrective yawing moment do not involve appreciable side forces and associated yaw angles, nor noticeable drag increases. The drag rudder is used only rarely for trim and its drag is therefore unimportant."

The tip fins previously used were favorable since they gave the largest yawing moment due to the longest arm (half wingspan). However, when used simultaneously, they caused tip-stall which in the case of a sweptback, led to a whip-stall (tip-stall, whip-stall). The first attempt to eliminate the whip-stall was applied on BKB-1A design.

Until that time, the only solutions for directional control were split flaps or spoilers placed on the tip of the wing, which precluded the placing of the elevators at this location. They had to be shifted to the center of the wing, with the resulting undesirable properties explained in the chapter "Pitch Control."

The Canard

Due to the absence of a tail in a canard configuration (Figure III-9), two rudders were placed at the trailing edge of the wing, close to the center. When they were actuated simultaneously at a certain deflection angle, they could produce opposite yawing moments which greatly decreased their effectiveness. This arrangement also has the inherent bad properties already mentioned in the description of the flying wings.

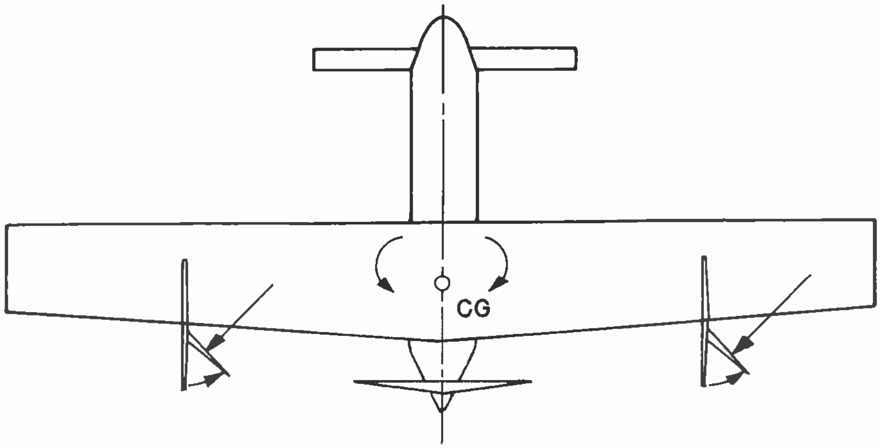


Fig. III-9

The Bird

The bird exercises lateral control by twisting the wingtip in the direction of the desired bank. This is similar to moving the aileron up on the airplane. Sometimes, especially at low speeds, birds with tails twist their tail also. Since only one wingtip is twisted the bird has no adverse yaw. This sometimes is a problem with airplanes at high angles of attack. By twisting the wingtip, the bird also produces greater drag at the inside wingtip, causing it to turn in the direction of the roll. This way the bird does not need a vertical tail to turn. Every turn is well coordinated with one single control surface which, when not needed, is an integral part of the wing without producing additional drag.

The Kasper Wing

The principles of bird lateral control discussed above have been used on the Kasper Wing but since a movable wing mechanism would be too complicated, different means were used to obtain the same aerodynamic results.

Having placed the elevators close to the wingtips, a new problem arose: how to control the roll. The simplest solution appeared to be the use of the elevators as ailerons, but when used as ailerons they produced adverse yaw; that is, opposite to the desired roll direction. Airplanes with a tail counteract this yaw with the vertical fin and rudder. A flying wing without the damping effect of the tail is susceptible to yaw. A solution had to be found to eliminate the "adverse yaw."

First, let us analyze the causes of the "adverse yaw." The down aileron, especially at high angles of attack, causes about three times as much drag as the up aileron for the same deflection angle. A partial cure in common practice is to make the movement differential, but in the case of a tailless airplane this is not sufficient. We have to substantially decrease the drag on the down aileron and increase it on the up aileron. One way to decrease the drag on the down aileron is to install a tab at the trailing edge which will move up whether the aileron moves up or down. All that remains is to find a suitable mechanism which will do the work. The simplest geometric solution would be two tangential circles with different radii.

When the hinge line of the aileron is in the center of the bigger radius and the lever actuating the flap is shorter, it will always pull the flap "in" regardless of the direction of travel by the aileron. This kind of tab has another advantage. When the ailerons are used as elevators, the tab increases the response in the "up," low speed position and decreases it in the "down," high speed position. This equalizes pitch sensitivity regardless of the airspeed. See Figure III-7.

IV INTERACTION

A completed airplane is in many ways a collection of compromises. Therefore the most important task is to evaluate which features of the airplane design are vital for satisfying the primary requirements such as aerodynamics, stress, economy, cost, range, useful load, etc. Then we have to consider the secondary, tertiary and other features and evaluate benefits derived against possible detrimental effects. All the detrimental effects have to be carefully studied and minimized as much as possible. The ideal situation would be when the secondary side effects are also beneficial.

I call this study "INTERACTION."

I will use, where applicable, the conventional airplane design and compare it with the Kasper Wing design. Although all of the statements have been made in other chapters, their review and summary is worthwhile.

CONVENTIONAL AIRPLANE (CROSSTAIL)
LONGITUDINAL AND DIRECTIONAL STABILITY AND CONTROL

The primary purpose of the horizontal stabilizers is to counteract the pitch moment created by the lift and weight of the plane. It keeps the plane in equilibrium like the counterweight on a scale (Figure IV-1).

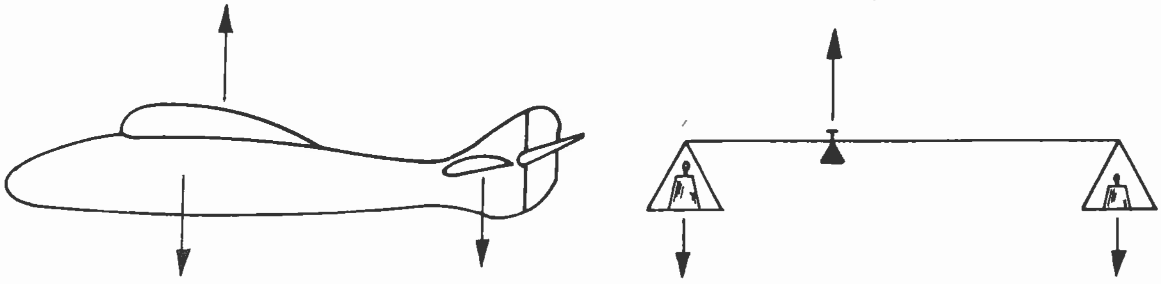


Fig. IV-1

A scale can be in equilibrium but still oscillate, and so can our airplane. In the same manner as the friction forces on a scale will dampen the oscillations, so will the aerodynamic forces return the plane to its initial position when disturbed by a gust or by the pilot. We call this the "dynamic stability." The stabilizer's primary purpose is achieved, to some extent, when the plane will return to its initial attitude after a number of decreasing oscillations. When the dynamic stability is insufficient the pilot has to be the ultimate "stabilizing factor" or, as in the case with airliners, a mechanical substitute, the "automatic pilot," takes over to improve the unstable system.

A check of secondary effects reveals:

1. The continuous down force on the stabilizer and its weight are loading down the airplane all the time, causing a bending moment in the fuselage, requiring a heavier construction of the latter. This download reduces the airplane's capability to carry useful load by about 30%.
2. The horizontal stabilizer is producing drag all the time. This requires more horsepower.
3. The forces on the horizontal stabilizer are produced by the forward speed of the airplane, so below a certain speed the plane loses its balance and stability. The remaining two forces, lift and weight, will tend to nose the airplane down sharply. When insufficient altitude is available, this means the end of flying. The skill of the pilot cannot prevent the crash because the elevator forces are a function of speed and the effectiveness of the elevator is lost.
4. During pull out at high speed, the horizontal stabilizer and the elevator act as a restraining force producing torsion in the wings. Because the bending moment is at a maximum during pull out, and likewise the torsion, the wing has to be stressed for those additional requirements, resulting in an additional weight penalty.
5. For a nose high attitude, like at take-off or landing flare, the elevator must induce downward forces, increasing the total load of the plane. This is the reason why airliners, which on take-off for long flights are loaded to capacity, have to dump fuel in order to lighten the plane when an emergency forces them to land.
6. When the horizontal control surfaces are mounted at the lower part of the vertical control surfaces, they screen the upper part of the rudder, producing difficulty in spin recovery.
7. The cross formed by the vertical and horizontal control surfaces increases the total drag greatly due to interference.

DIRECTIONAL CONTROL

The vertical controls, fin and rudder, are supposed to produce directional stability, but the type of stability they produce is an oscillating one, similar to the action of a weather vane. The only stabilizing factor is the pilot or, on bigger airplanes where the pilot is fed up with the continuous "kicking," a yaw damper which has been installed to take over the kicking.

The detrimental secondary effects are:

1. Continuous drag, even when the rudder is not in use.
2. When the rudder is used it produces the required yaw, but in addition it causes a roll opposite to the yaw direction because the force on the rudder is above the neutral axis of the fuselage. It could be called "adverse roll." This roll is not great, but it is not helping either.
3. The entire crosstail, being located in the most turbulent zone behind the fuselage, requires much greater surface area compared to control surfaces located in undisturbed flow. This adds to the weight and increases the drag.

ROLL STABILITY AND CONTROL

In order to obtain roll stability we use dihedral. This works all right as long as the wings are straight. With sweptback wings it is a different story. The dihedral changes with the angle of attack, and this change is in the wrong direction. The airplane needs maximum roll stability at landing and take-off when it is close to the ground, and control response is low because of the slow speeds. A sweptback wing's dihedral becomes negative at high angles of attack and the plane becomes unstable, requiring continuous corrections with the ailerons which have decreased response due to the low speed. Besides the required roll moment, the ailerons are also producing a yawing moment in the opposite direction to the roll. This is called "adverse yaw." To some extent this yaw is reduced by the differential movement of the ailerons; usually 1:3. The remainder has to be counteracted with the rudder. This requires the use of all three controls; ailerons, rudder and elevator, in order to make a turn. The slight increase in speed required for a turn is done with the elevator. The combined action of all the controls is called the "coordinated turn." The amount of the particular control pressures to be applied varies from one airplane to another. This is one of the reasons that FAA requires a certain number of hours in a new type of plane before giving the pilot authorization to operate it.

As we can see, the standard controls have limitations and cost a reduction in performance and payload. The greatest disadvantage is that they cease to function below the "minimum control speed" and limit the plane to an angle of attack between 15 and 20 degrees. In addition to the above mentioned disadvantages the standard controls fail completely in two flight conditions. These conditions are "deep stall" and "dutch roll."

1. Deep stall can occur when the CG moves aft of the CP. This happens easily on sweptback wings when the wingtips stall. This causes a movement of the center of pressure inboard and, due to sweepback, forward. The angle of attack is above the stalling angle of the horizontal stabilizer which make it inoperative. The forward speed drops below the minimum control speed, and the plane "mushes" down, out of control. There is only one known case where a highly skilled pilot, using flaps, spoilers and power, was able to take the plane out of the deep stall. Altitude loss during this maneuver was in the order of 20,000 feet.
2. Dutch roll is also peculiar to sweptback wings. It occurs when a turn at a high angle of attack is attempted.

The higher speed of the outer wing, coupled with the greater projected areas in the turn, causes a sudden increase of drag which produces a yaw in the direction opposite to the turn. The drag reverses and the process repeats itself in the opposite direction. Due to the swaying motion at high angles of attack, a great turbulence is created behind the wing which makes the crosstail airplane controls inoperative.

The Kasper Wing and the arrangement of its controls are shown in Figure IV-2.

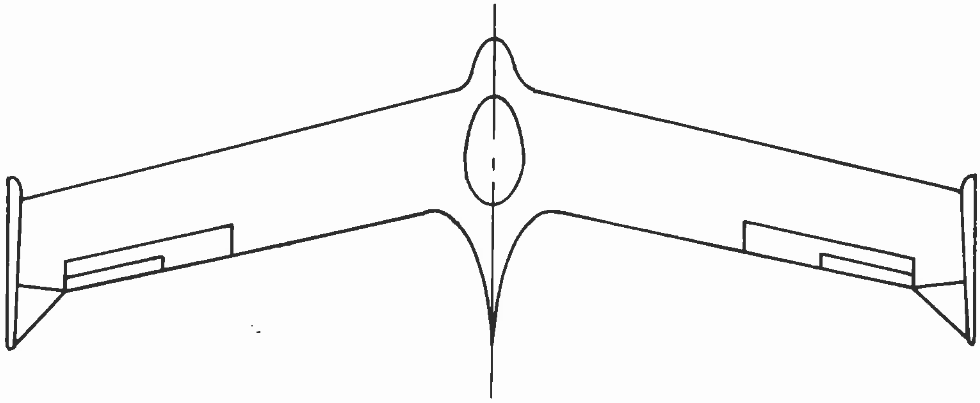


Fig. IV-2

With this arrangement of the controls, the following conditions have to be maintained in order to obtain the proper response when the controls are actuated.

1. The shape of the wing has to be rectangular, not tapered. The reason is that pitch control is affected by changing the spanwise lift distribution. We must have lift at that part of the wing where the elevators are located. The wingtip stabilizers help to obtain an elliptical lift distribution. When the elevators are moved up or down, this elliptical lift distribution changes to a more or less triangular one, causing a considerable shift of the CP (center of pressure) inboard or outboard and, due to sweepback, forward or rearward.

2. The airfoil has to have a reflexed profile, which is characterized by a stable CP position. The CP does not wander chordwise with a change of angle of attack. No airbrakes or spoilers are allowed on top of the wing because they would cause an unpredictable change in the lift distribution with resulting random pitch response.
3. Moderate Sweepback, 13° - 15°, is necessary. In order to transfer the spanwise distribution of the lift caused by the elevator movement into forward and back movement, we need to sweep back the wing. The birds obtain this forward or rearward movement of the center of lift by moving the wings backward or forward for fast or slow flight.

   The amount of movement of the center of lift is a function of the sweepback angle, but the pitch response depends on the vertical distance between the CG and CP. The greater this distance is, the greater should the sweepback be in order to obtain the same angular response. Therefore high-wing airplanes need more sweepback and mid-wings less, for the same pitch sensitivity. Low-wings can only be used in the shape of a gull wing. This solution has the additional advantage of greater roll stability.

4. *Endplates and tip rudders.* In order to decrease tip losses we use endplates at the wingtips. Additional benefits from them are that they can be used as directional stabilizers because 4° - 5° is the flow deviation at the upper surface of the wing at 13° sweepback angle. By toeing the endplates in 4° - 5° their drag is cut to a minimum. When they are inclined 30° - 45° to the vertical a configuration is obtained which assures a high roll stability independent of the angle of attack. Therefore dihedral, which changes with the angle of attack on a sweptback wing, is no longer needed.
5. The primary function of the elevon is to control pitch and roll. As we mentioned earlier the anti-balance tab eliminates adverse yaw when the elevons are used as ailerons. However, when we use the elevons as elevators, the anti-balance tabs increase the sensitivity at low speeds and decrease it at high speeds, making the pitch response of the plane independent of forward speed.

   An additional benefit of the elevons used as elevators near the wingtips is that they cause a variable washout, from the start of the elevators to the tips. The washout increases at high angles of attack (slow speed), and decreases at low angles (high speed). This property eliminates the need of a built in geometric washout.

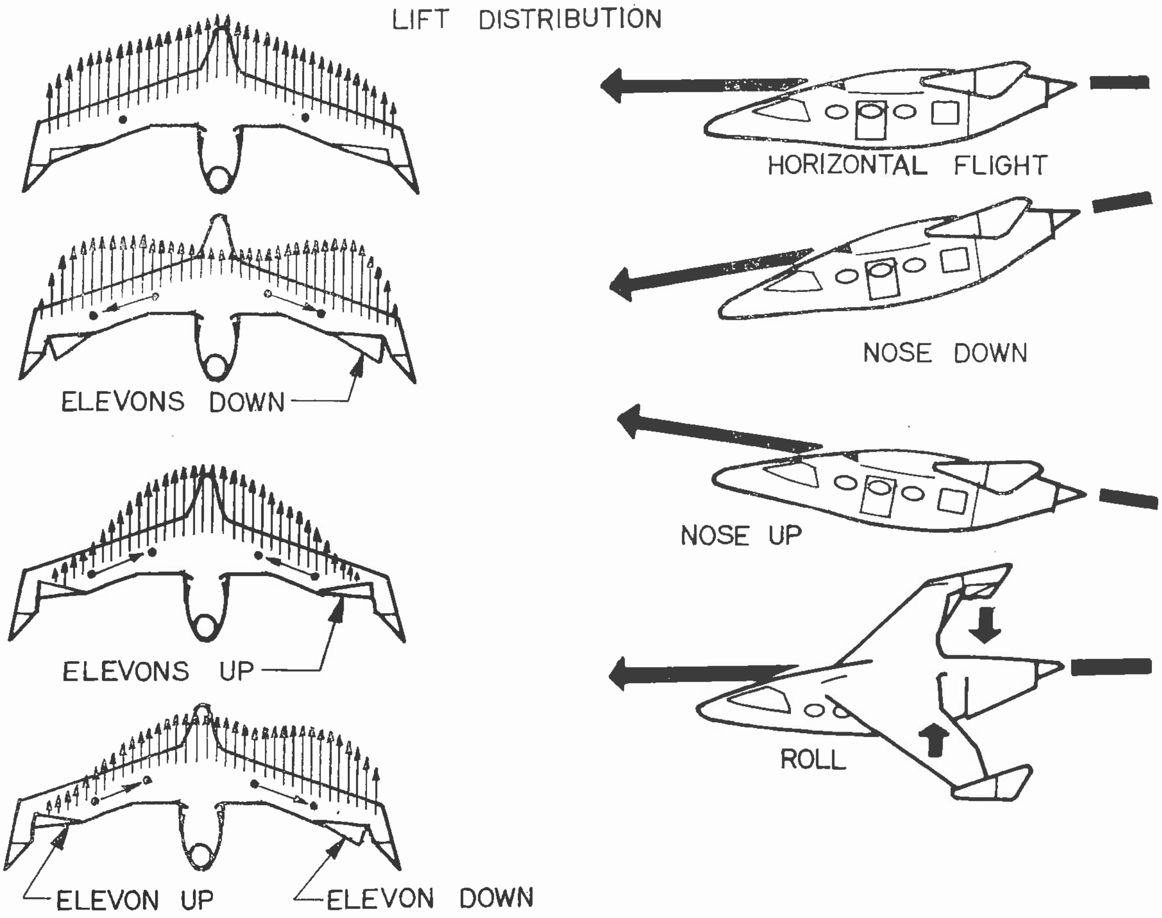
   An additional benefit is obtained when we are pulling out at high speed. The forces in the down direction created by the elevators at the wingtip are changing the almost elliptical spanwise lift distribution into a triangular one, which greatly decreases the bending moment of the wing.

   The forces applied at the wingtips are opposite to the lift and change the cantilever wing momentarily into a tip supported wing. Figure IV-3 illustrates these points.
6. *Horizontal tip stabilizers.* Their action is similar to the elevator. Moved up, they produce nose up moment which counteracts any moment created by the forward movement of the CG. When the angle of the tip stabilizers is changed the spanwise lift distribution moves the center of lift spanwise due to the sweepback. Thus the lift can be moved in the direction of the displaced CG to maintain a constant static margin. Locating the stabilizers at the wingtips causes a permanent washout in their up position. This, combined with the higher angle of attack at the center of the wing, forms a conical shape which creates the so-called "drogue stability" in the pitch plane. This stability is augmented at slow speeds by the up position of the elevators, reaching its maximum at stall speeds and slower. This is contrary to the crosstail plane where the "dynamic stability" at the stall angle approaches zero.

By explaining in detail the interaction between the different design features of the Kasper Flying Wing, I have tried to sweep away the preconceived notions and incorrect data that have previously been distributed to unsuspecting students of aeronautics. The concepts that I have presented are facts, not theories only, proven by flying and testing Flying Wings of my own design.

My research also serves to explain why earlier designs of flying wings and tailless airplanes by others, both in this country and in Europe, were failures and based on wrong assumptions.

I hope that my fellow airplane and glider designers are open-minded enough to accept what I have offered as a contribution to their search for a safer and better air vehicle. Let us fly like a BIRD!



THIS REPRESENTS A CANTILEVER WING, WHERE THE MAXIMUM BENDING MOMENT IS $\frac{wl^2}{2}$

WITH THE ELEVATORS THEORETICALLY AT THE WINGTIP, THE MAXIMUM BENDING MOMENT IS ONLY 1/4 OF THE VALUE ABOVE

THE ACTUAL ELEVATOR EXTENDING INBOARD TO QUARTER SPAN, MAXIMUM BENDING MOMENT IS 1/16 OF THE UNRELIEVED CANTILEVER WING

Fig. IV-3

V MODIFICATIONS TO EXISTING DESIGNS

Based on the presented analysis and the experience gained while flying the Kasper Wing gliders, an ideal safe and economical airplane of the flying wing type can be built which will make all the existing crosstail airplanes obsolete. However, realistically and practically we have to consider the economic impact. In our country alone there are thousands of airplanes flying. Every manufacturer has a great number of crosstail airplanes in stock or on order. Their designs are certificated by FAA. They have enormous capital invested in tooling. When a new "ideal" safe and economical airplane appears, nobody would buy a crosstail airplane and the airplane industry would go bankrupt. This will have an adverse impact on the economy. The present owners of crosstail airplanes would be least affected. They could still continue flying their outdated airplanes.

There is however an intermediate solution. The experience gained from the Kasper Wing concept could be used to improve the economy and the safety of the already built airplanes. For instance, the ratio of maximum to minimum speed could be increased from the existing 1.8 - 3.3 to 5.0 - 7.0, which would greatly improve the safety. The useful load which is now 60% of the empty weight could be increased to 100%. The drag could be greatly decreased by eliminating the tip vortex and the interference drag of the crosstail. Consequently perhaps a slower but less costly road could be followed, still leading to the "ideal" plane. Instead of "revolution" the change would be an "evolution," which is less painful and more acceptable to the Aircraft Establishment.

The following modifications can be incorporated in the existing crosstail planes in order to improve their safety and ecomony.

1. Tip plates.
2. Tip rudders.
3. Anti-adverse yaw tabs on ailerons.
4. Wingtip stabilizers.
5. Elevons.
6. Moderate sweepback.
7. Reflex profile.

The gains will be as follows:

1. *Tip plates*
   a). Increase the lift coefficient by about 30%.
   b). Decrease the drag coefficient by about 30%.
   c). Increase the effective aspect ratio by about 70%.
   d). Increase the roll stability when inclined 30° to the vertical.
   e). When toed-in, the yaw stability is greatly increased, making the vertical tail obsolete.
   f). Increase the roll effectiveness of the ailerons at high angles of attack.
2. *Tip Rudders*
   a). By hinging the rear part of the tip plates, they can be utilized as rudders. The aerodynamic balance portions in front act as spoilers replacing the ailerons. When both rudders are deployed they function as air brakes.
   b). When the endplates are inclined, the hinge line has to be slanted by the same angle in order to permit the aerodynamic balance to move parallel to the base line of the profile and also prevent the rudders from creating "adverse roll."
3. *Anti-adverse yaw tab on ailerons*
   a). Eliminates adverse yaw when used on ailerons.
   b). When used on elevators or elevons increases sensitivity at low speeds and decreases sensitivity at high speeds.
4. *Wingtip horizontal stabilizers*
   a). Increase the pitch stability, providing, especially at low speeds, drogue stability.
   b). Their combination with the tip plates provides a partial venturi, which accelerates the airflow at the tip and cancels the wake, which produces the tip vortex.
   c). When used on sweptback wings, eliminates whip-stalls caused by tip-stalling.
   d). When actuated from the cockpit, they can be used in auxiliary elevators or ailerons, providing redundance to the standard pitch and roll controls.
   e). They could be utilized for pitch and roll trim.
5. *Elevons*
   a). When elevons are used as elevators, in addition to the elevator action they provide a variable washout which increases with increasing angle of attack. At high speed, when it is not needed, the washout becomes zero or even negative. This action eliminates the need for a geometric washout.
   b). The elevator forces the change in lift distribution from rectangular to triangular, eliminating the need for tapered wings. At the same time the maneuvering forces are directed opposite to the lifting forces and so they unload the wing. This permits designing the spar for the gust forces only
6. *Moderate Sweepback*
   a). Increases the directional stability of the plane.
   b). Increases the effectiveness of the horizontal tip stabilizers and the elevons by providing a greater moment arm for the forces generated by them.
   c). In concert with the elevons, permits the shift of the center of lift forward and back, providing a pitch controlling force which is independent of forward speed. Increases the static stability at low speeds.
7. *Reflex profile*
   a). Improves the pitch stability.
   b). Assures a fixed position of the center of lift and thus eliminates the need for a horizontal stabilizer on the tail. Helicopter blades are pitch stable without a tail.
   c). When sweptback and elevon controlled, it permits the shift of the center of pressure back and forth assuring the change of the angle of attack up to 90°, which allows the formation of the "vortex" on the upper surface. The vortices form at an angle of attack of from 35° to 40°.

VI THE KASPER WING

THE REASONS LEADING TO THE DEVELOPMENT OF THE KASPER WING CONCEPT

The comparison between the airplane and the bird was the reason for building and testing the Kasper Flying Wing glider.

The glider was conceived to obtain a flying wing with the degree of stability and controllability approaching those of the birds. In the following pages I will list the differences between the airplane with the crosstail and the bird with the tail folded in flight, or even no tail at all.

1. The airplane's low speed is limited by the minimum control speed and the so-called stalling speed, below which the airplane ceases to be a flying machine. The pilot, when the altitude does not permit free fall until the flying speed is restored, is punished for this "mistake" by death or injury.

   The bird does not have this limitation of minimum speed to be flyable and controllable.
2. The airplane operates within a 20° range of angle of attack while the bird's operating range extends up to 90°. This is best demonstrated at landing, when they come first to a full stop at an incredible angle of attack, and then gently settle down under full control to a pinpoint landing. As for the airplanes; they never land, they fly in, requiring miles of runway. The birds also circle in currents in a nose high attitude, without lateral inclination, well above the 20° which is the usual stalling angle of the airplanes.
3. Under maneuvering loads, including pull up, the airplane's wings are loaded additionally and the wings bend up. In this situation the maximum bending and torsional stresses are developed in the airplane wings. To withstand these loads the wings have to be built much stronger, and consequently heavier, than would be needed for normal level flight, when they have to withstand only the forces of nature, the air gusts. In order to reduce some of these loads, the wings are tapered to obtain a triangular load distribution, which decreases the bending moment at the root by 1/6. However, we pay for this deviation from the ideal load distribution (elliptical). The wing efficiency drops to about 70%.

   The bird's wings can take only bending moments. They have no torsional stiffness at all, and the stress coefficient is only 3.5. Measurements have shown, however, that birds can pull out of a dive at upwards of 9 G's, without their wings breaking off. The top view of the bird's wing shows that not only are the wings not tapered, but they are wider at the tip than at the root. This causes a load distribution more rectangular than elliptical, so the wing efficiency increases to 120%. What is the answer to the mystery of a wing, built to withstand a 3.5 G load, which can take a 9 G load without breaking twice over?

4. The pitch and directional stability of our airplanes are linear functions and therefore they require damping forces, without which they would be oscillating systems. This damping is produced by the forces on the crosstail, generated by forward speed. When the speed decreases, those damping forces continuously decrease until they are not sufficient to keep the airplane in the desired attitude. As a result, the stability and controllability of our airplanes decrease with decreasing speed, and limit their operating attitude to the "magic" 20° angle of attack, beyond which the so-called stall is waiting, and the flying ends suddenly.

   The bird's pitch, yaw and roll stability is based on a stable second degree system, and increases with decreasing speed; therefore, the bird can hover fearlessly, before settling for landing.

5. In order to decrease the landing speed of our airplanes, the designers are changing the shape of the profile, adding flaps on both ends of the profile, sometimes adding suction or blowing, and increasing the area of the wing to obtain a greater lift coefficient. But at the same time, to counteract the nose-down moment which those gadgets are producing, the elevator is deflected up. This compensating action increases drag. In other words, the wings are provided with complicated systems to increase lift, while the tail is loading and slowing the plane down.

   The bird, at landing, is spreading its tail and moving it down, which produces additional lift. What keeps its nose up even when the speed is near zero?

6. When the airplane is flying level the forces on the tail are still present as download and drag in addition to the weight of the tail and its supporting structure. The drag alone often reaches 30% of the total drag of the airplane. When the controls are used, they transfer their forces by means of the fuselage, bending and twisting it. So not only the wing is stressed but also the fuselage. This requires strong and heavy structures.

   The birds have no controls on the tail, so the body is stress-free. No additional downloads or drag are produced. The lift generated by the wing can be 100% used to carry the bird and the additional payload. The result is that our airplanes have a ratio of payload to empty weight of 60%, while the bird's ratio is 120% with 30% less drag.

Those are the most obvious differences between our crosstail airplane and the birds. Some of them can be called poor design or poor economics, but the really horrifying situation is the number of fatal accidents due to stalling. The birds cannot afford that because they rely on flying for their living. They would need to lose speed only once in their life and within one generation they would be wiped out.

As a pilot with thousands of hours of flying, from airplanes to airliners, I decided to study this contrast. Being also an aeronautical engineer and aircraft designer, I had the advantage of being able to avoid the problem of communication among the three specialties, which would have required at least three people. I recognized from the beginning that the Bird Designer is far superior to any of the aircraft designers — me included. So I started with the study of the bird's design and the bird's flight. Often I encountered seemingly impossible phenomena, which appeared to violate the existing aerodynamic laws. I determined that those laws are incomplete and related to the very limited possibilities of our airplanes. For instance why worry about the phenomenon of birds hovering when we cannot duplicate it. We closed our minds while looking every day at those incredible flights, we chose not to see them.

This typical attitude is characterized in the popular statement among aerodynamicists, "According to the aerodynamic laws, the bumble bee cannot fly, but it flies anyway. Probably it is not sufficiently educated in aerodynamics." This sounds funny but in reality it is pathetic. We admit that we are so sure of our knowledge that we deny the obvious and close our minds to the phenomena which our senses are transmitting to us.

In order to test what I learned, two possibilities existed. The usual one, through wind tunnel tests, and the other a flying test-bed. The first was out of reach. No respectable scientific establishment nor industry would risk money to test ideas which often were contrary to the established rules.

So I chose the other way. The BKB-1 glider was designed and built. Test-flying was no problem. I did not need a special test pilot or any insurance to cover the risk. I flew it myself. The plane behaved like it should; very stable, very sensitive on controls. It was so sensitive that I had to install a differential pitch steering to make it comparable to existing planes. The controllability and stability did not decrease with decreasing speed. Then I started testing it at low speeds. At 40 mph minimum speed obtainable with the elevator up, the glider's sink rate increased to 600 per min. but remained very stable and the response to the controls remained as lively as at normal speeds. I doubted that I had reached the stall speed. In order to test this I glued a tuft to the trailing edge of the wing to be able to observe whether I reached separation, which is the prerequisite to a stall. At 40 mph the tuft curled up and the plane's sink rate increased to 600 ft. per min. The stick was still in a forward position. I pulled gently back and then incredible things happened. The sink rate decreased, the variometer indicated 200 ft. per min., speed dropped to 30 mph, stability increased, and control was as good as before. The tuft curled forward and remained stretched forward, indicating a strong flow opposite to the flight direction. The estimated angle of attack was 30°.

I repeated this several times. The same phenomenon took place after the stall was passed. After landing I did not dare to tell others the story because no one would have believed it. No explanation for this behavior could be found within classic aerodynamics. In order to obtain more information about this reverse flow, I glued four rows of tufts on top of the wing from the center to the tip. Fellow pilots were joking that I put feathers on the wing, and kept snickering behind my back. I also added five pounds of lead to the tail in order to reach an even higher angle of attack. Again the tow was normal. In free flights the plane had a slight tendency to turn in the direction of the heavily tufted right wing so that a slight pressure on the left rudder was in order. The tow went to 5000 feet. I wanted to be sure that no currents were present. It was a hot day and the inversion level was at 2000 feet. Normal sink rate, now measured with three variometers independently hooked up, showed 200 ft. per min. at 50 mph indicated. An angle of attack indicator was also added. The conditions were nearly ideal for such a test. At 40 mph the last row of tufts started curling up, showing separation. Sink rate increased to 600 ft. per min. As I pulled the stick back the last row reversed first, the second followed and with full stick back the third row of tufts changed to the forward direction. The first row, positioned at 25% of chord, remained in the flight direction but moved up tangentially to the leading edge curvature. The speed dropped to 20 mph, angle of attack indicator showed 35°, but the most astonishing phenomenon was indicated by the variometers. The sink rate dropped to 100 ft. per min.; only half the minimum sink rate in normal flight. All three instruments indicated the same. This was supposedly impossible. I speeded up to normal flight regime to test whether there was not some lift in this area. The air was smooth as before, sink rate 200 ft./min. — no lift. I turned back, went into the ultra slow speed flight and the same phenomenon was repeated. I kept circling for 5 minutes and then tapped the altimeter. The height lost in this time correlated with the indicated low sink rate. There could be no doubt; an unknown phenomenon was keeping the glider afloat at half the sink rate and half the stalling speed. This needed a lift coefficient of 3.15. Where it came from was a puzzle. What was even more astonishing was that in straight flight, in this overstall configuration, the glider had a tendency to turn to the left, opposite to the tendency in normal attitude. Not only had the lift mysteriously increased but the drag on the wing roughened up with the tufts was less.

Analyzing the whole phenomenon, one thing was clear: past the stall, a vortex was forming on top of the wing.

Back to the birds. In slow flight the bird not only moves its wings forward to obtain the forward shift of the center of pressure, but also the tip feathers are spread. I knew already that the cascade thus formed is opposite to the one we arrange with flaps for slow speed. Ours is a down cascade; the birds have an up cascade. This means the air flowing from the bottom to the top of the wing is directed forward, against the airflow; this "wrong" arrangement now becomes right. It is reinforcing the vortex.

Now I was sure that I was on the right track. But the hard part remained to be done. What did I know about the vortex movement? Next to nothing. The first book on Aerodynamics in its 460 pages had only four pages with rudimentary explanations of the vortex phenomenon. Back to the library. After one and a half years and some 140 special publications on the vortex phenomenon in five languages, I still could not find the definition of the essence of the vortex. All the publications described test results in the laboratory, dealing with vortices in some peculiar restricted circumstances, often neglecting the basic laws. No wonder! All the scientists were interested in was to avoid or destroy the vortex which not only was a nuisance but was not manageable. And what was even worse, it was upsetting the existing laws based on the potential flow theory. The fact that, in nature, potential flow does not exist and that every flow ends up in vorticity did not in the slightest bother the scientists. They made up their minds that only potential flow is useful, and vortices are to be avoided at any cost. The cost was high, like everything which is contrary to the laws of Nature. Once I accepted the vortex as the normal and natural kind of flow in liquids and gases, I attempted to write down the laws which rule vortex flow. In May 1970 the brochure "Vortex Motion and its Application to Aircraft" was written. I still did not dare to publish it. It was "too far out."

I tested the response to my discoveries by predicting the results for various arrangements and restrictions imposed on vortex flow by researchers. These predictions were always correct. I could even explain the previously unexplainable happenings when the test data did not initially indicate the anticipated.

The communications with my fellow engineers ended with funny looks. At best I was credited with some extraordinary capabilities as a pilot who could fly below the stall speed or who had sheer luck in designing a glider.

Nevertheless I have now decided to build a powered version of the glider, well-equipped with instruments and continue the tests. The way is hard but it must be done, not for the economic advantages that this flying wing will bring, but for saving the lives of the pilots. Removing pilot fatalities and injuries caused by the slight mistake of flying below a certain speed, often due to external circumstances such as negative gust or engine failure, is well worth the effort.

CONTROLLING THE KASPER WING

The stability around all three axes of the Kasper wing is based on the stable "drogue" system. The attitude is a function of the geometric configuration which changes with the positions of the control surfaces, establishing a new stable attitude. (See Chapter II Stability.)

The attitude change is achieved by aerodynamic forces acting on the control surfaces. Due to this double action the control sensitivity of the wing is greater than that of the standard plane, where only the aerodynamic forces are responsible for changing the attitude of the plane.

Consequently, some pilots, especially those who acquired the "automatic response" flying the standard planes, will overcontrol the Kasper Wing, especially in pitch. They are accustomed to the so-called double movement, which is necessary for standard planes but will cause pitch oscillations in the Kasper Wing. The only way to stop this is to stop moving the stick back and forth.

In order to illustrate the control response of the Wing, we can compare it to the response of an automobile to the movements of the steering wheel and the gas pedal.

Pitch control: speed increase — speed decrease

Car: Push gas pedal forward and hold.
Wing: Push stick forward and hold. When the wing acquires the desired angle of attack, hold it because this is the new stable attitude. It will not continue in a downward curve like the standard plane will. The same single movement back will lower the speed. Again the warning: *No double movements.*

The reaction of the Wing to the back and forth movements of the stick can be best illustrated by assuming that the stick is rigidly connected to the plane (Figure VI-1).

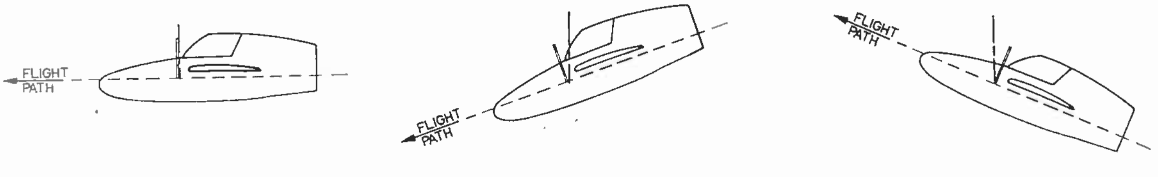


Fig. VI-1

The standard plane's response is as illustrated (Figure VI-2).

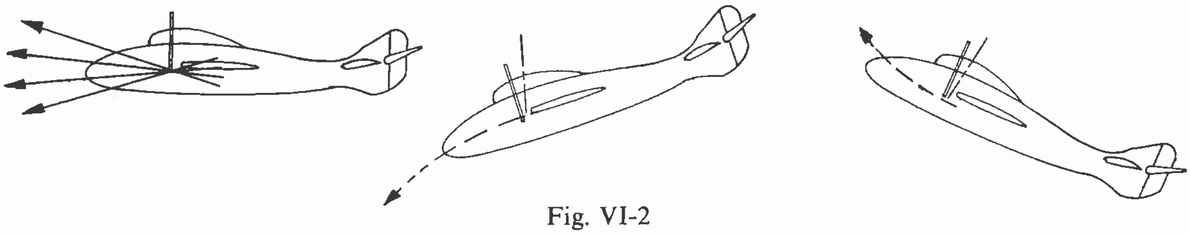


Fig. VI-2

Here the double movements are necessary in order to keep the plane on a straight path. But in the case of the Kasper Wing, double movements will cause PIO, pilot induced oscillations, which can be stopped only by stopping the stick, preferably in the neutral position.

Roll and yaw control

The independent rudders in the wing have a triple action, when used as rudders. See Figure VI-3.

1. When the rudder is deflected, at first the aerodynamic balance spoils the lift at the wingtip, causing the wing to roll in the direction of the deflected rudder.
2. Then the rear part of the rudder comes into action, causing high drag at the wingtip and forcing the plane to swing (yaw) around the tip.
3. The spoiling action of the aerodynamic balance screens off the horizontal stabilizer, which in straight flight produces a downward force, which when cancelled, causes the plane to pitch down slightly. This triple action eliminates the necessity to use all three controls to make a coordinated turn, as is the case with the standard plane. Stepping on the rudder produces a perfect coordinated turn with the ball in the center. Any additional use of the ailerons will cause overcontrolling.

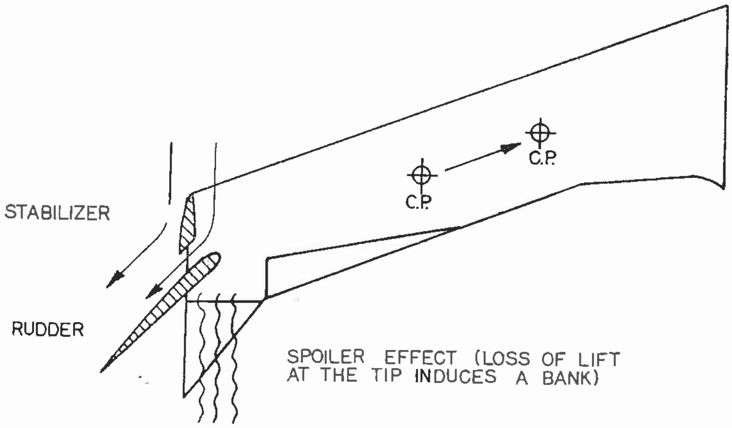


Fig. VI-3

The rudder action can also be compared with the steering of a car. In order to make a turn, we turn the wheel in the desired direction and hold. To tighten the curve we turn the wheel more. To straighten the turn we return the wheel back to the neutral position. We never use double movement, unless we want to rock the car from side to side.

The ailerons are used only for the following maneuvers:

1. Side slip, to hold the wing down.
2. Spin, to cross control.
3. Crosswind landing, to keep the wings level.
4. To hold the plane level when flying below the so-called "stall speed."

All other roll maneuvers are executed with rudder alone. When, by mistake, the aileron is also used to remove the plane from a turn, it will result in overcontrolling and the plane, instead of ending the roll level, will swing to the other side. When this is repeated the plane will enter a swinging motion from side to side.

So forget the ailerons for rolls and turns. You can use them to wave the wings sidewise to greet your girlfriend on the ground.

WEIGHT AND BALANCE OF THE KASPER WING

Weight and balance is the proper positioning of the center of gravity in relation to the aerodynamic forces of lift and the horizontal stabilizer, so that the result is a perfect balance in pitch of the airplane.

In conventional airplanes the moment arms of the aerodynamic forces, in relation to the center of gravity, are great and so is the inertial moment in pitch. Therefore, if a plane is not perfectly balanced, the effects in flight are small and can be overcome by adjusting the horizontal stabilizer up or down. The forces acting on a very long arm can overcome quite a significant misplacement of the center of gravity in relation to the center of lift.

For the flying wing the conditions are different. The inertial moment in pitch is very small. When the aerodynamic forces are close to the center of gravity with a very short arm for pitch control, and when, in the case of sweepback, the total lifting force of the wing moves back and forth, depending on the positions of the elevators, the wing is very sensitive. Any displacement of the CG in relation to the center of pressure will cause great amounts of pitch displacement. The solution to this problem is made more difficult by lack of wind tunnel data about lift distribution on a rectangular wing with tip plates.

Fortunately there are some significant factors which make the proper balance simpler than on conventional crosstail planes.
They are:

1. The profiles are reflex-shaped which characteristically have a constant pressure center, independent of the angle of attack. The percentage of the chord where the center of lift is located is constant for a given profile.
2. Because the planform is a rectangle, the spanwise lift distribution, once calculated, can be expressed as a percentage of the half span and easily transferred to any span.

   Thus the position of the center of pressure can be given as a percentage of the chord and span. The projection onto the center of the plane is only a function of the sweepback angle β.
3. The wing has no washout, so the lift distribution does not change with the angle of attack when deflected by gusts.

   (The profiles I used on the Kasper Wing were NACA 8-H-12 and FX05-H-126, which is an improvement of the 8-H-12 made by Dr. Wortmann. Both profiles have the center of pressure located at 28% of the chord.)

   The spanwise lift distribution for a rectangular wing with endplates, for a clean wing, is shown in the graph of Figure VI-4.

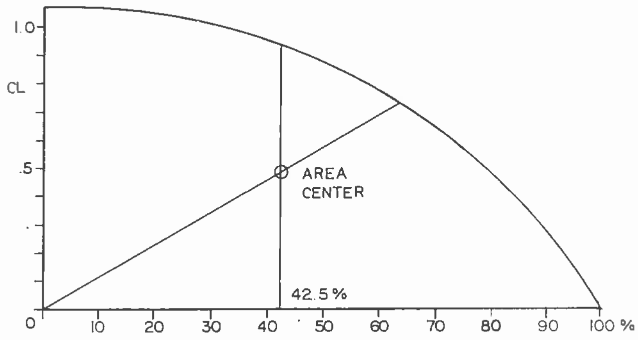


Fig. VI-4 Percentages of half span.

The center of pressure is at 42.5% of the half span, measured from the centerline of the airplane. These two factors, profile and planform, remain constant. For both profiles, the location of the CP remains a constant percentage of the chord. The only variable will be the sweepback angle.

Let us derive the formula which will be used to calculate the position of the center of lift at the symmetry axis of the wing (Figure VI-5).

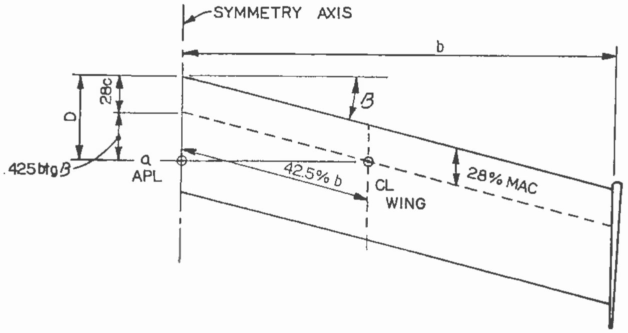


Fig. VI-5

where b = half span
c = chord length in the flow direction
CP = center of pressure
D = distance of lift L from the leading edge, at the center line of the wing.

$$\underline{D = .28c + .425b \times tg\,\beta}$$

Because three sweepback angles are commonly used (13°, 15°, and 20°) their tangents are listed to facilitate calculations.

tan 13°	.23087
tan 15°	.26795
tan 20°	.36397

After we have established the location of the CL along the axis of the plane, we need to locate the CG.

Theoretically it should be at the same position as the CL. However the Kasper Wing has horizontal stabilizers at the wingtips which only move up. This will shift the CP only forward. This will accommodate any forward shift of the CG due to payload distribution or fuel shift.

Any back shift of CG has to be compensated for by deflecting elevons down, which will limit the control capability of the wing in pitch.

In order to permit a limited rearward movement of the CG we should initially locate it forward of the center of lift and compensate the nose down movement with an up position of the horizontal stabilizer, for about one-quarter of the total movement. From the experience learned with two gliders and several models it was found that the total CL movement is about 25% of the MAC. A location of the CG at 4% to 8% of the MAC forward of the CL will give a sufficient safety margin in case the CL is mislocated. This leeway is about double the allowance we have for conventional crosstail planes, in which the total allowable movement of the CG is about 12% of the MAC.

When the designer of a new wing finds that the CG is not at the desired point, he can relocate the CL by changing the span or the sweepback angle or both.

After calculating the CL position for a given wing, it is recommended strongly that, as a check, a graphic solution be made to detect any possible error.

VII VORTEX MOTION AND ITS APPLICATION TO AIRCRAFT

INTRODUCTION

In everyday life many fluids can be observed to exhibit recognizable rotary motions apparently following well defined rules.

In physics, such fluid rotations are called vortices, eddies or circulations and when occurring outdoors, in wind or water, are called whirlpools, maelstroms, tornadoes, or cyclones.

In ancient times, Homer described the twin whirlpools of Scylla and Charybdis and Leonardo daVinci has left many fascinating studies of swirling waters.

In modern times, when the behavior of fluids was assuming greater importance in the design of machines such as turbines and airplanes, these rotary movements were often considered detrimental, and much theoretical research and experiment was done to eliminate them.

However, the majority of this research was done for a particular kind of vortex. In a particular application, experiments were generally made in a two-dimensional form which, as will be seen later, is not the ideal way to study a true vortex.

Stemming from these experiments and from additional theoretical studies, many rules were formulated but, because they were based on differing particular circumstances, they were sometimes quite contradictory.

In more recent times, the study of vortex flow has become more important because of the negative effects it usually has on airplanes and because of the need to develop the fewer beneficial applications such as vortex generators and flow constrictors.

In order to deal effectively with vortices a thorough knowledge of the phenomenon is needed.

An attempt will be made in the following pages to:

1. Summarize the existing knowledge of the vortex phenomena.
2. Define the basic laws which govern its behavior.
3. Indicate how a vortex can be used to generate more lift.
4. Indicate how vortex control can be made to reduce drag.
5. Indicate other uses for a vortex.

THE FORMATION OF A VORTEX

A simplified model of a vortex is shown in Figure VII-1.

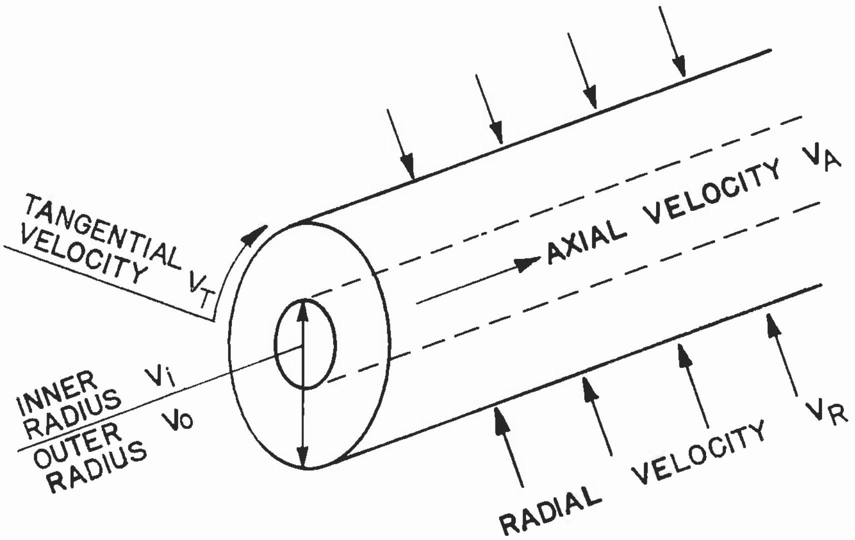


Fig. VII-1 — Vortex model used in analysis.

It must be understood that all the velocity components, V_T, V_R and V_a, are components of a single speed which the particle possesses. The components vary with time as the particle moves in a three-dimensional spiral (Figure VII-2).

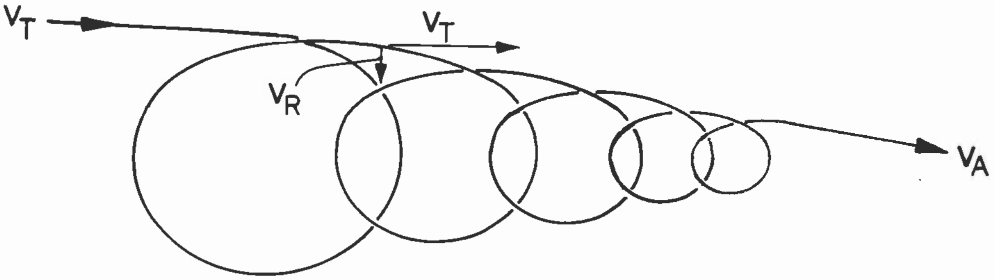


Fig. VII-2

A picture of a vortex can be formed by visualizing a spiral spring, fed tangentially into a corner with velocity V_T, and pulled out axially from the center with velocity V_A (See Figure VII-3).

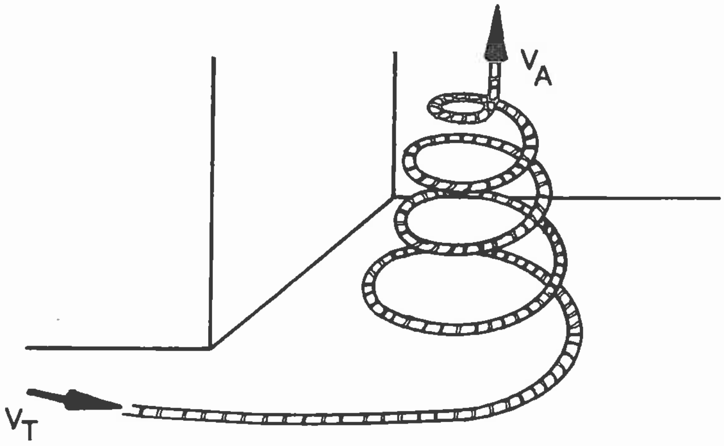


Fig. VII-3

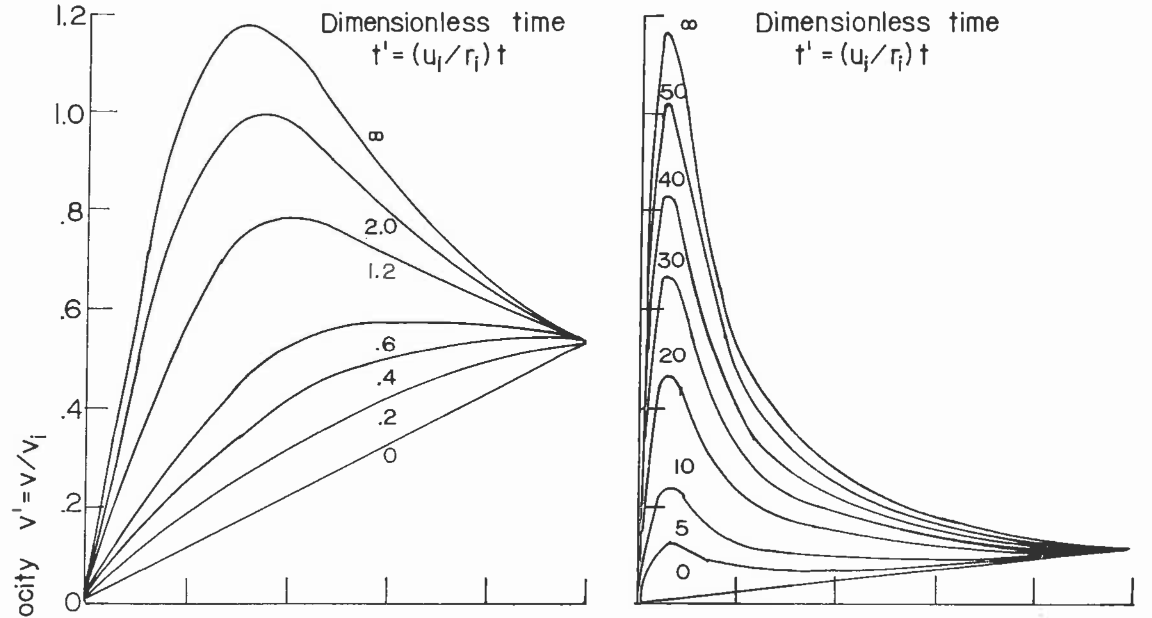
It will be seen that this vortex movement can be initiated from either end and will set in motion the whole chain of effects ending, after a suitable time, with a fully developed vortex.

THE FULLY DEVELOPED VORTEX

A fully developed vortex has to obey several rules:

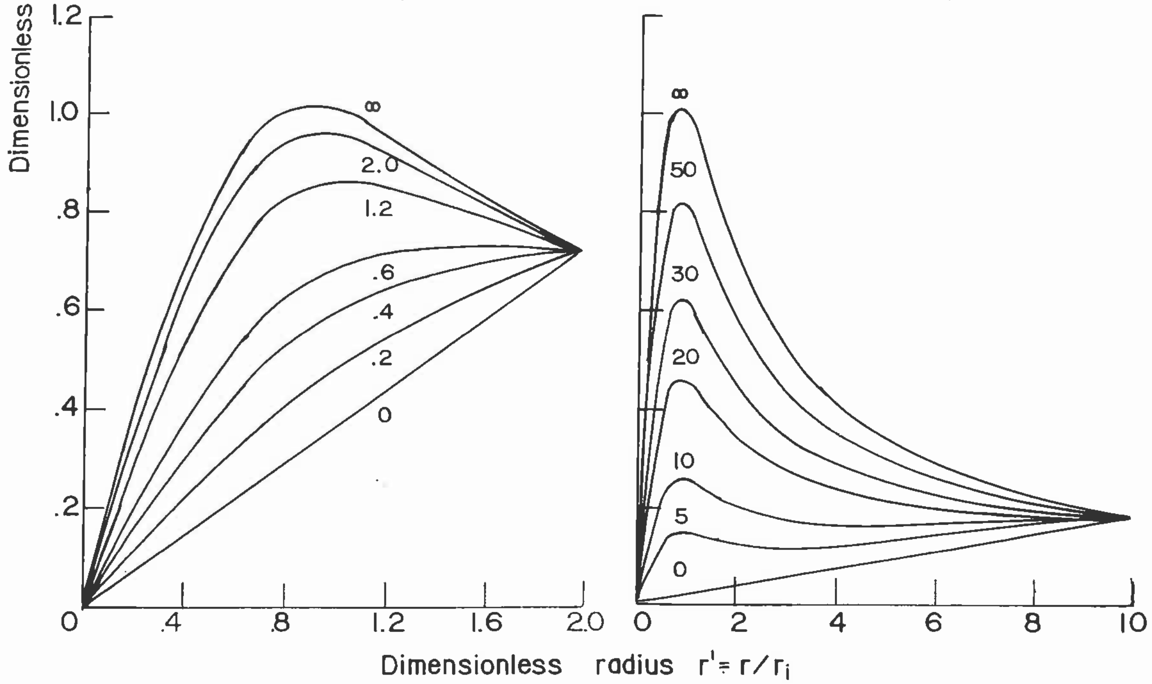
1. The rate of feed must equal the rate of bleed. This is called the "Entrainment-Detrainment" rule.
2. The tangential speed component, V_T, is proportional to the outer radius divided by the inner radius, r_o / r_i, in the outer annular part of the vortex and obeys the law of constant angular momentum.
3. The diameter of the core is established when the momentum of the radial flow component due to pressure drop is in equilibrium with the momentum of the centrifugal forces due to the tangential speed component.
4. It has to begin with tangential flow and end with axial flow or vice versa.
5. Increase or decrease of the flow at either end of the vortex causes an increase or decrease of the inner tangential speed component according to the formula,

$$v1 = 1/v, \quad \frac{1 - e^{Rev^2/2}}{1 - e_R{}^{0}/_{2}} \quad \text{for } 0 = v^1 \quad 1$$



(a) Radial-flow Reynolds no. −6, ratio outer to inner radius, 2

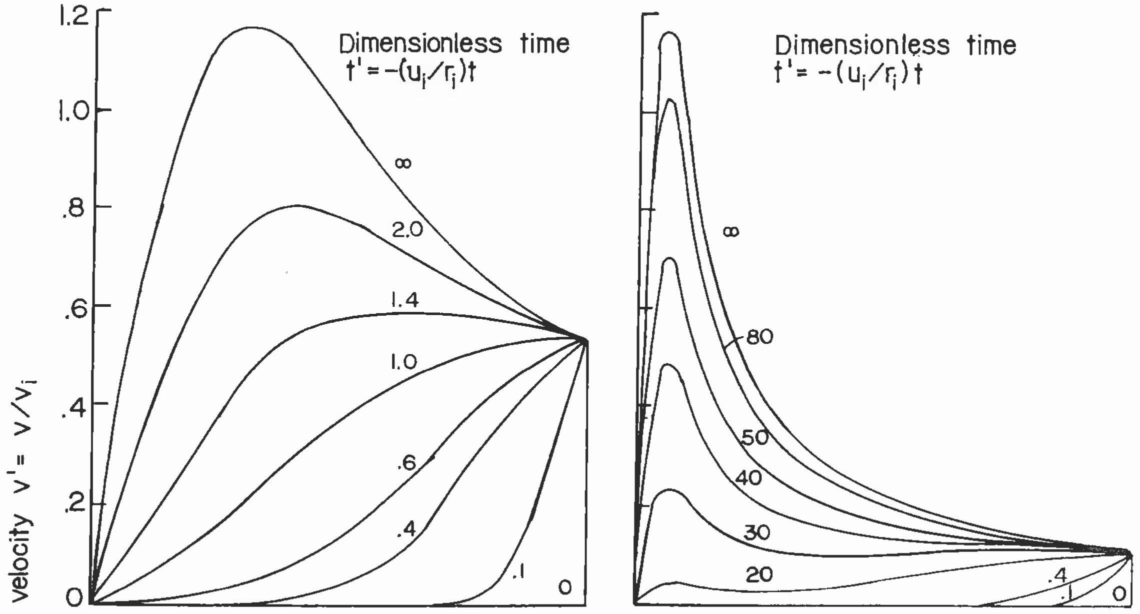
(b) Radial-flow Reynolds no. −6, ratio outer to inner radius, 10



(c) Radial-flow Reynolds no. −3, ratio outer to inner radius, 2

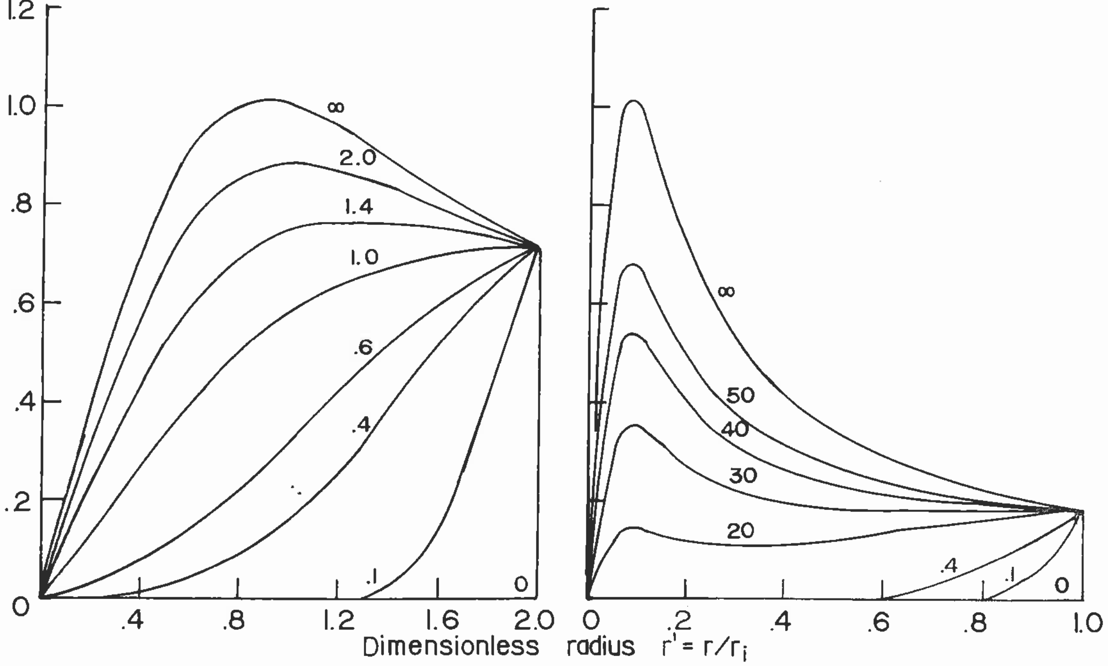
(b) Radial-flow Reynolds no. −3, ratio outer to inner radius, 10

Fig. VII-4 — Growth of vortex from initial wheel flow produced by radial inflow.



(a) Radial-flow Reynolds no.-6, ratio outer to inner radius, 2

(b) Radial-flow Reynolds no. -6, ratio outer to inner radius, 10



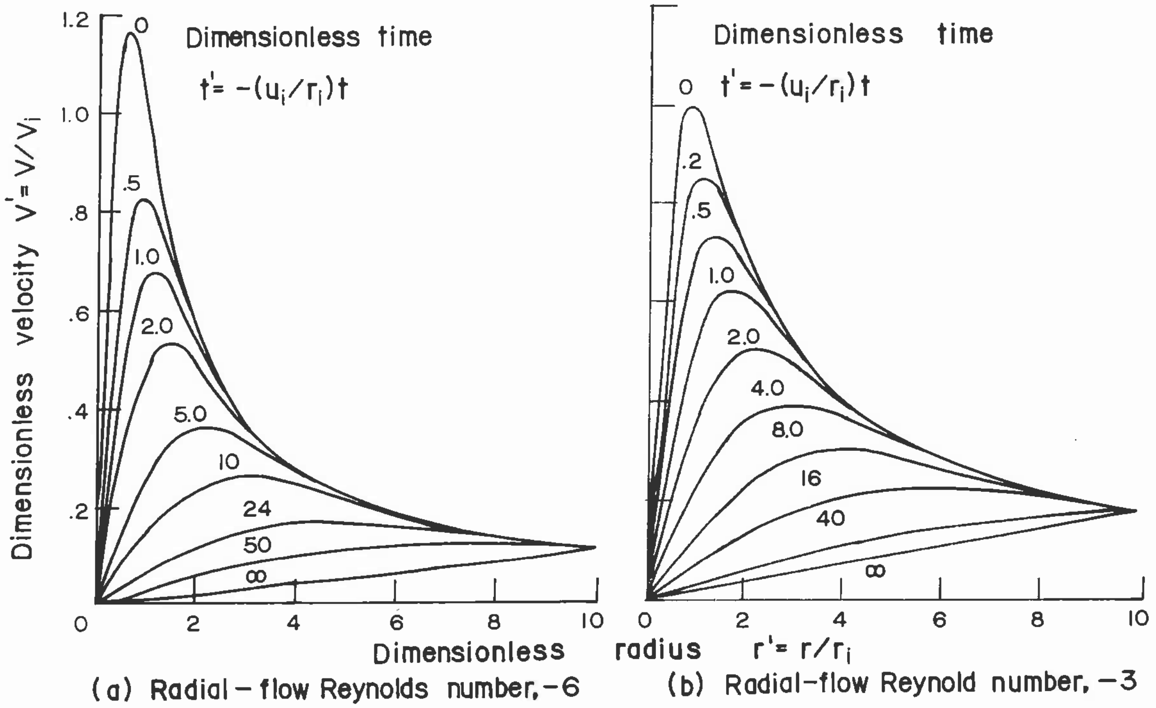
(c) Radial-flow Reynolds no.-3, ratio outer to inner radius, 2

(d) Radial-flow Reynolds no.-3, ratio outer to inner radius, 10

Fig. VII-5 — Growth of vortex produced by vorticity introduced at outer radius.

THE DECAYING VORTEX

Any interruption of flow at any point will cause the decay of the vortex downstream of the disturbance (Figure VII-6).



(a) Radial-flow Reynolds number, −6 (b) Radial-flow Reynold number, −3

Fig. VII-6 — Decay of fully developed vortex to wheel flow when radial inflow is reduced to zero. Ratio of outer to inner radius, 19.

THERMODYNAMIC EFFECT OF A VORTEX

The distribution of tangential speed V_T, pressure P, and temperature T, within a mature vortex is shown in Figure VII-7.

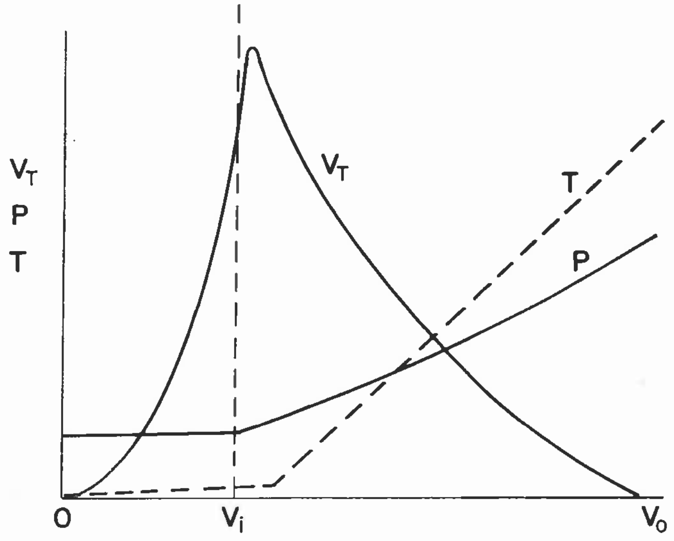


Fig. VII-7

Pressure decreases as the radius decreases from r_0 to r_i due to the increasing tangential speed component. This approximates to an adiabatic expansion which causes heat transfer from r_i to r_0. The air cools as it approaches the core and the heat remaining in the vortex expands the air volume. This causes an unconfined vortex to swell and a confined vortex to accelerate tangentially. It is this phenomenon that produces the driving power in tornadoes and dust devils. It has also been used to cool gases. By blowing gas tangentially into the closed end of a tube a closed vortex system is set up within the tube. Two outlets at the far end of the tube exhaust heated gas at the outer rim and cooled gas at the center, as shown in Figure VII-8.

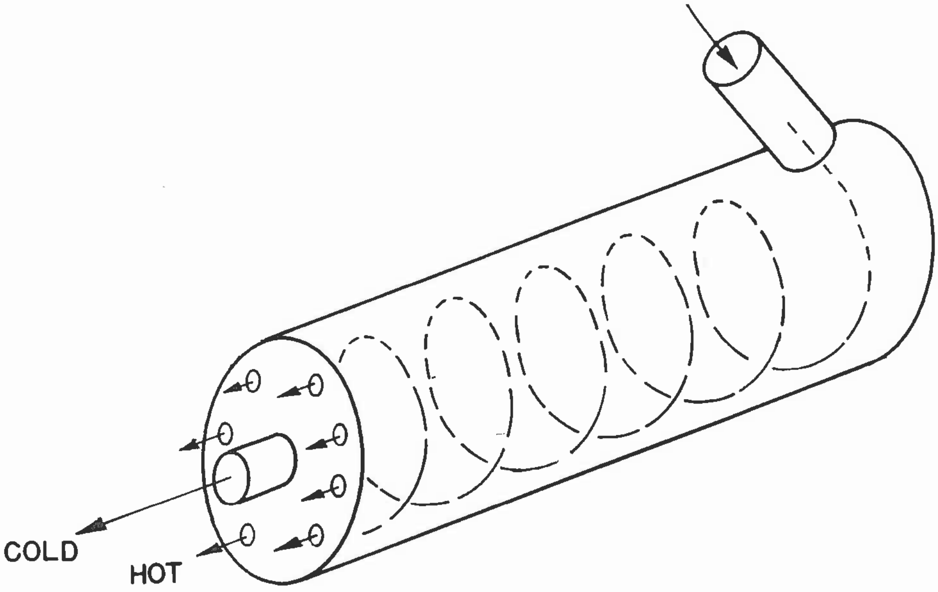


Fig. VII-8

THE APPLICABILITY OF THE VORTEX PHENOMENON TO THE AERODYNAMICS OF AN AIRPLANE

Delta Wing

Since the advent of Delta-shaped wings it was observed (Ref. 1, 2) that at high angles of attack more lift was generated than would result from the potential flow. On investigation it was found that a vortex was formed at the leading edge of each wing causing a spanwise flow which was faster than the forward speed of the plane (Fig. VII-9).

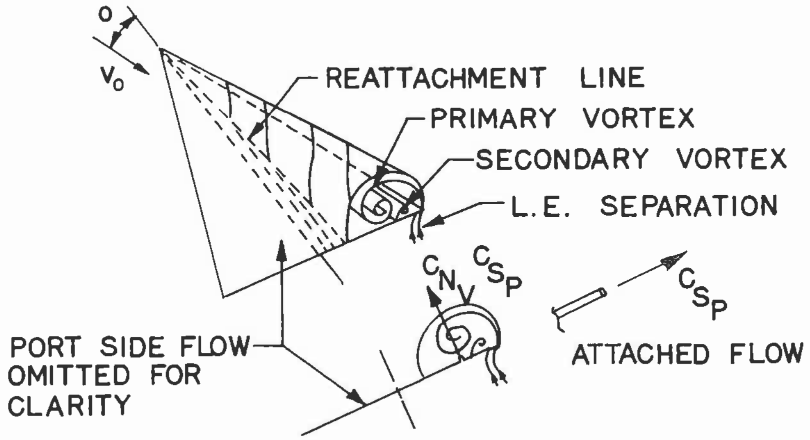


Fig. VII-9 — Illustration of vortex flow details and leading-edge suction analogy.

Measurements show (Ref. 3):

1. The total lift is about 100% higher than the potential lift at maximum angle of attack.
2. No stall occurred as the angle of attack was increased (Figure VII-10).

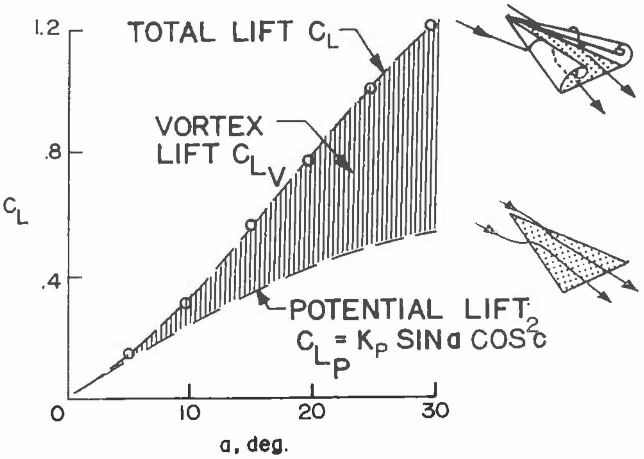


Fig. VII-10 — Illustration of the vortex lift for a 75° delta wing.

3. Lift increased with increase in aspect ratio (Figure VII-11).

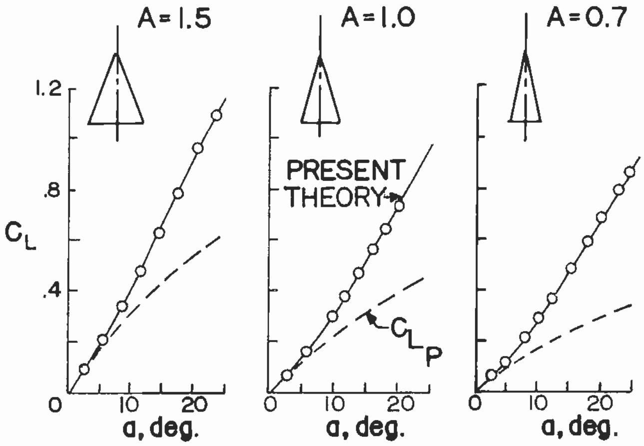


Fig. VII-11 — Comparison of present theory with experimental lift of delta wings. M = 0.

The total lift according to Polhamus' Theory is

$$C_L = K_p (\sin\alpha \cos^2\alpha) + K_v (\cos\alpha \sin^2\alpha)$$

where the first term is the potential lift and the second is the vortex generated lift.

The second term can be rewritten in the form

$$(K_p - K_p^2 K_i) \cos\alpha / \cos\Lambda \sin^2\alpha$$

where the constants K_p and K_i can be determined from an appropriate lifting surface theory and Λ is the sweepback angle of the leading edge from the lateral axis.

Straight or Swept Wing

At high angles of attack, at least 30-35 degrees, a sharp flow separation occurs at the crest of the airfoil upper surface. The airfoil is now acting as an obstruction in a free airstream and a vortex is formed as described earlier.

It forms a regular flattened vortex along the top of the wing as shown in Figure VII-12.

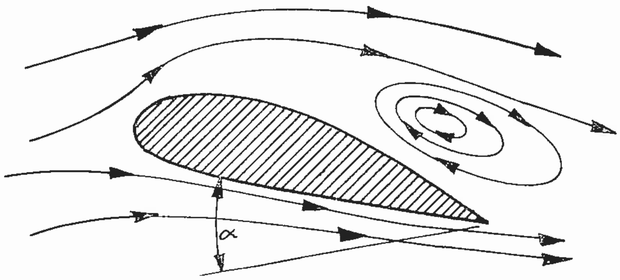


Fig. VII-12

This vortex has the following benefits:

1. It maintains lift at angles of attack well beyond the stall angle for potential flow.
2. Because of the forward flow of the air on the upper wing surface, the direction of skin friction drag is reversed.
3. The wing stability is increased because the aft movement of the center of lift generates a counteracting nose-down moment about the CG.

This phenomenon was first observed on the BKB-1A flying wing glider which was able to fly at very steep angles of attack.

CONTROLLING A VORTEX TO INCREASE LIFT

In order to generate the vortex the most important condition is to separate the flow at the crest of the leading edge. A high angle of attack causes this separation but there are other methods which may also be used.

A baffle at the leading edge may be used to produce a deeper leading edge curve and to provide a sharp edge from which the vortex will be generated, as shown in Figures VII-13, 14 and 15.

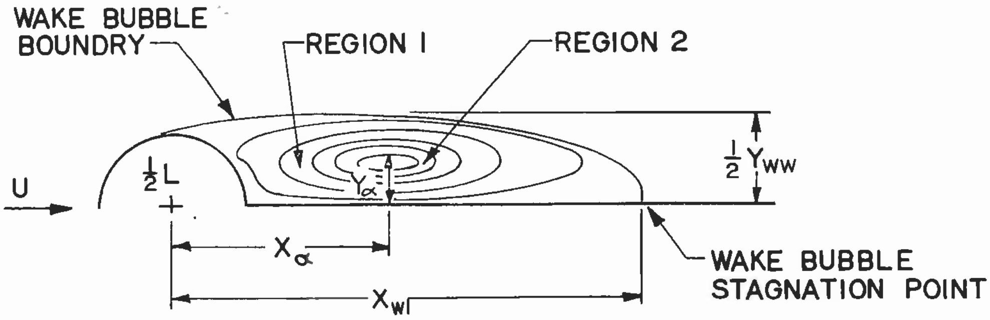


Fig. VII-13 — Typical wake-bubble.

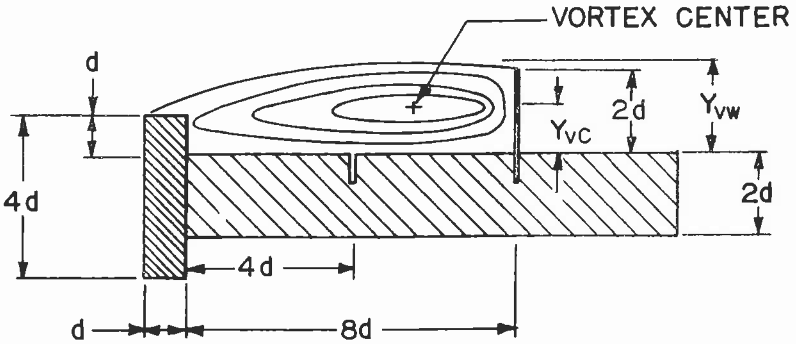


Fig. VII-14 — The confined cavity.

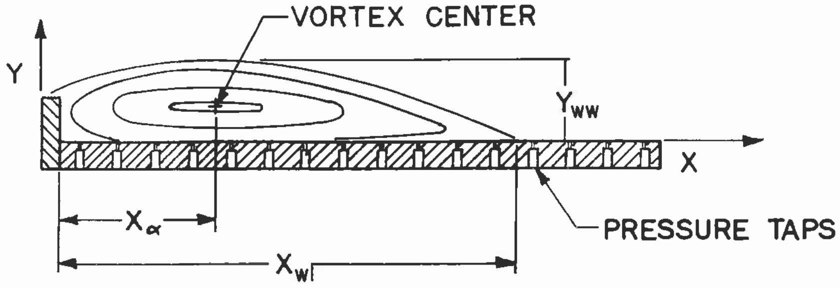


Fig. VII-15 — The backward-facing step.

However, this vortex will vary in size due to gusts affecting the airflow over the wing.

It can be stabilized by the configurations shown in Figures VII-16, 17, and 18, which show two types of trailing edge treatment limiting the size of the vortex and trimming off the variable surfaces.

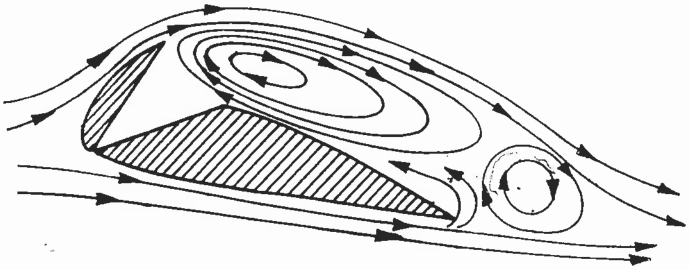


Fig. VII-16

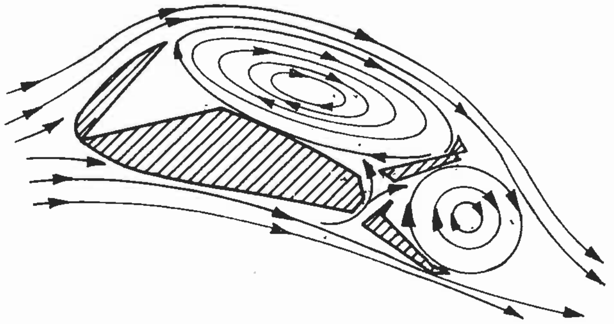


Fig. VII-17

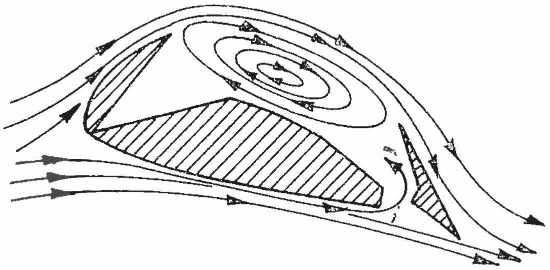


Fig. VII-18

The size of the vortex and the amount of lift which it can generate is thus limited to something less than the possible maximum, but the resulting vortex is of constant size and is very stable.

A further increase of vortex lift can be obtained by transferring moving air from the bottom of the wing to the top by means of slots, and reversing its direction of flow, as in Figure VII-19.

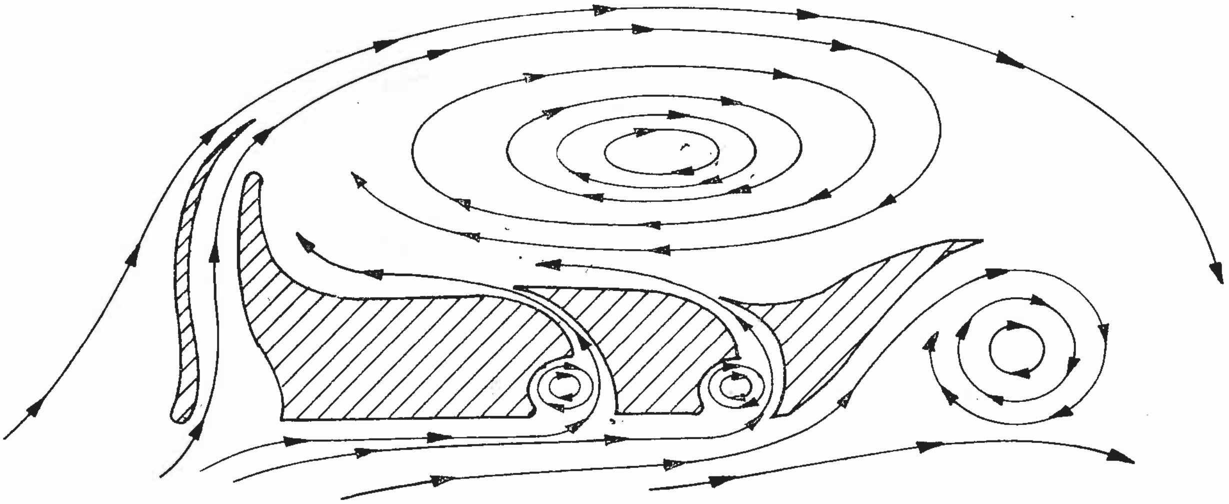


Fig. VII-19

Increasing the mass of air flowing through the vortex, which is confined between the wing top surface and the external potential flow, will increase the tangential speed, V_T, in the vortex, according to the continuity law ($VA = V_1A_1$), thus increasing the pressure drop on the upper wing surface and increasing lift.

At the same time, the speed of the airflow along the underside of the wing will decrease. A portion of the air mass flowing past the underside will be transferred to the upper side, leaving a smaller, and therefore slower, mass of air to pass beneath the remainder of the underside. With reduced velocity the air will generate more positive pressure on the under surface and thereby increase the lift.

CONTROLLING THE TIP VORTEX TO REDUCE INDUCED DRAG AT HIGH SPEED

A significant part of the drag of an airplane is the induced drag at the tips of the wing. It is caused by the air flowing from the bottom to the top of the wing due to pressure difference. In order to decrease this flow, various wingtip shapes have been designed to equalize the pressure. However, with a rigid wingtip this can be done only at one single angle of attack. According to the formula

$$C_{d_i} = \frac{CL^2}{\pi\,AR} = .318\ \frac{C_L^2}{AR} \quad AR = \text{aspect ratio}$$

the induced drag should decrease with C_L and for $C_L = 0$ should be 0. But in reality the tip vortex resulting from induced drag never is zero. This drag becomes even more pronounced at high speeds even though C_L is lower. This indicates that there must be another phenomenon influencing the tip vortex formation and its influence has to be proportional to the speed of the airplane. Let us isolate the tip vortex. When we assume the vortex is formed by the tangential flow only, it cannot develop into a proper vortex because the other element, axial flow, is missing. Without the axial flow, spiraling air could never form a vortex for miles behind the aircraft. As the wingtip moves through the air, suction is created at the trailing edge. It is filled with air flowing rapidly and axially forward in order to fill the void behind the wing. This is known as the wake. This phenomenon can be easily observed on ships, where the wake follows the vessel. All the necessary elements for a complete vortex, the axial flow and the spiraling flow from the bottom and the top, unite to form a perfect vortex. Because the axial flow (wake) increases with speed, it will compensate for the decrease of the rate of spiral flow with decreasing C_L.

In order to prevent the formation of a tip vortex, we have to eliminate the condition which generates it. As we have observed, the tip vortex is initiated by creating a suction at the trailing edge of the wingtip which induces an axial flow in the direction of flight, similar to a vortex in a draining bathtub. Having identified the course of this vortex we can devise means to prevent its formation. To stop the tip vortex, the low pressure and forward directed flow have to be eliminated. This can be accomplished by increasing the pressure behind the wing by means of blowing to the rear. Some solutions are shown in Figures VII-21, 22 and 23. Figure VII-21 shows a cuff on the top of the wing with vectoring action, accelerating the air at the trailing edge of the wingtip.

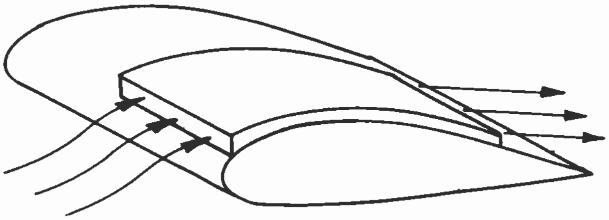


Fig. VII-21

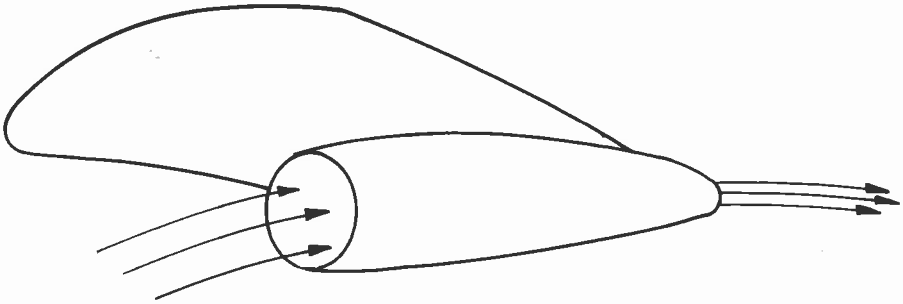


Fig. VII-22

Figure VII-22 shows a conical device to increase the velocity at the trailing edge. A jet of air is created by blowing through an internal tube exiting at the trailing edge of the wing in Figure VII-23.

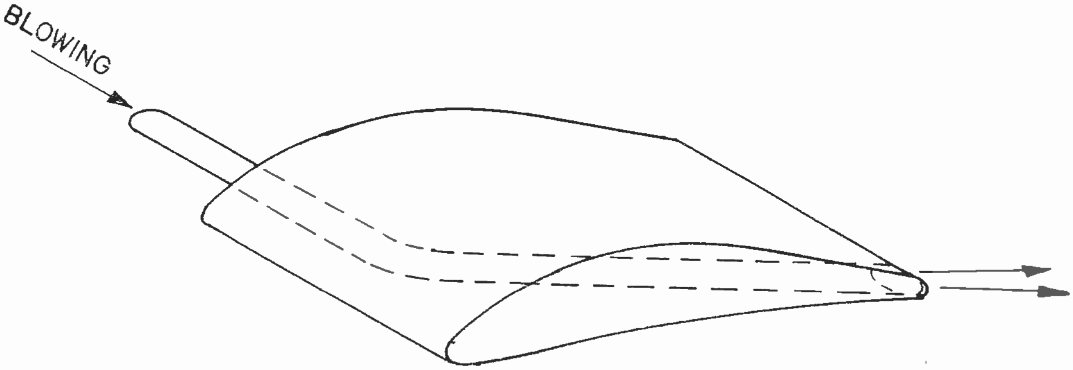


Fig. VII-23

THE VORTEX AS AN AIRFLOW DEFLECTOR

The vortex, being a steady self-contained phenomenon, does not readily mix with flow in other directions. When a vortex is exposed to a potential flow at any angle to its axis it will deflect the potential flow much like a solid body, but with considerably less drag. See Figure VII-24.

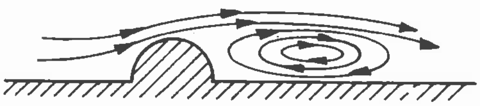


Fig. VII-24

For instance, this can be applied to engine intakes where an annular vortex can be generated by blowing jets of air to restrict the throat opening without the use of physical barriers (Figure VII-25).

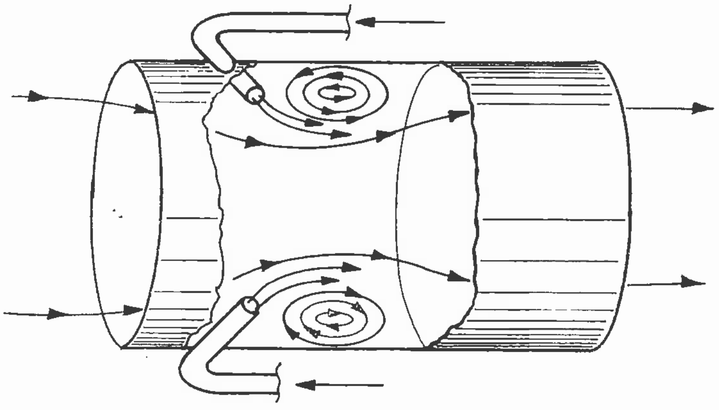


Fig. VII-25

THE VORTEX AS A CENTRIFUGAL PUMP

When a vortex is flattened, the speed, V_r, being proportional to V_1 / V_0, will increase at the flattened portions. If a deflector is placed near the maximum V_r, part of this high speed air can be bled away from the vortex in the manner of a centrifugal pump. See Figures VII-26, 27 and 28.

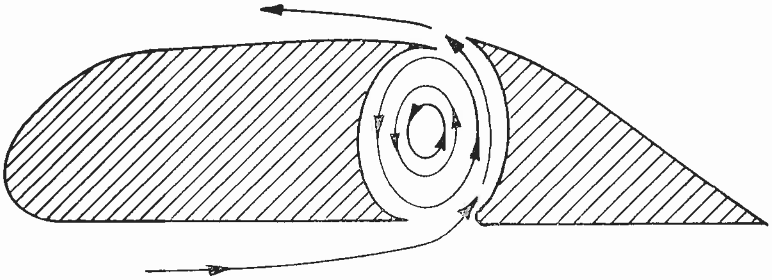


Fig. VII-26

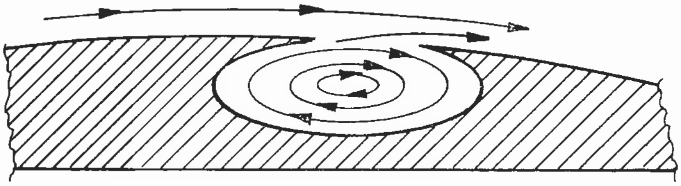


Fig. VII-27

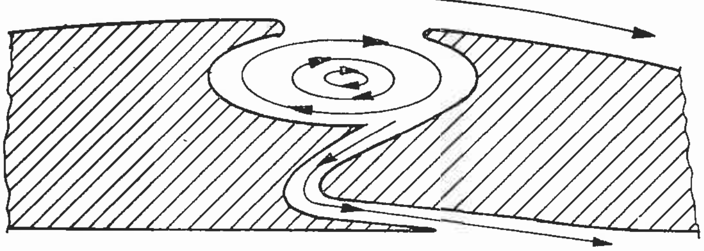


Fig. VII-28

CHANGING THE SHAPE OF A PROFILE WITH A VORTEX

Because a potential flow will go around a vortex and because of the fact that a vortex tends to assume a somewhat circular cross section, it can be used to form a changeable upper surface of a wing.

Figures VII-29, 30 and 31 show how a movable cusp at the leading edge and an adjustable inverted flap at the trailing edge will cause the vortex to change shape, as required to vary the effective camber of the initial profile.

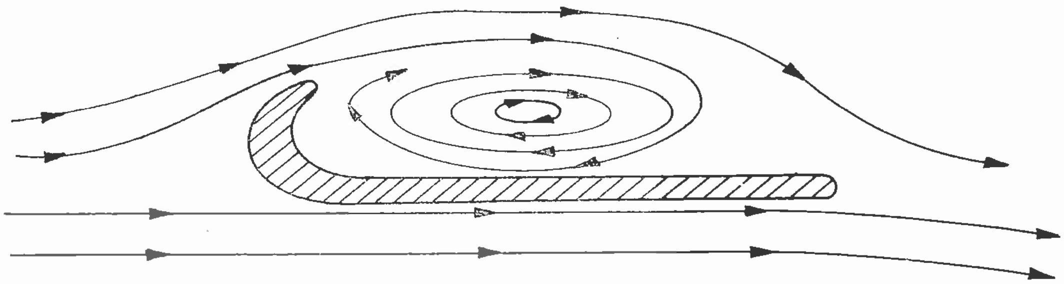


Fig. VII-29

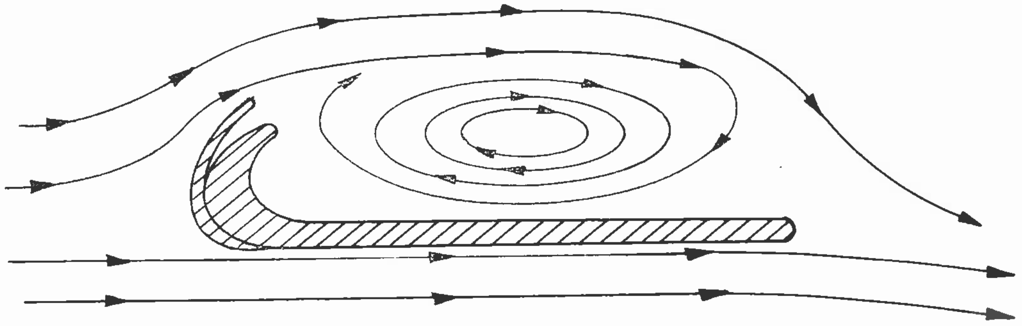


Fig. VII-30

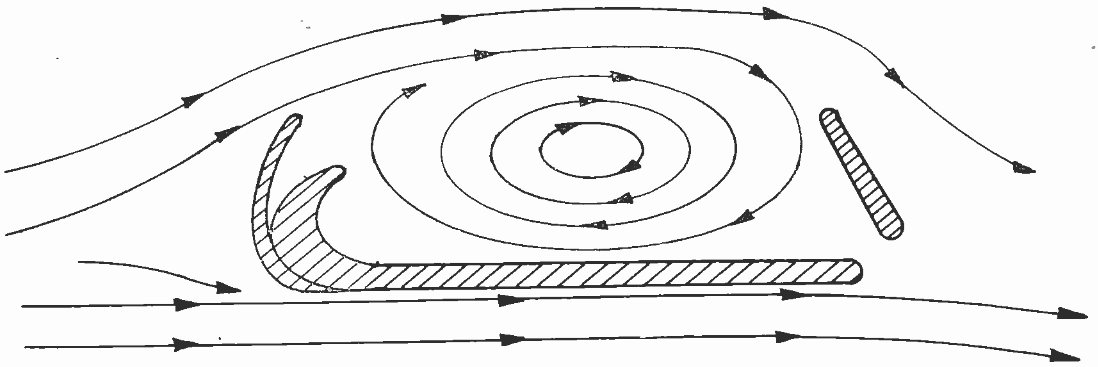


Fig. VII-31

LIST OF SYMBOLS

V = Tangential Speed

u = Radial Speed

v = Axial Speed

P = Pressure

T = Temperature

r_i = Inner radius of core

r_o = Outside radius of vortex

t = Time

r' = r_o / r_i

A = Aspect ratio b^2/S

Re = Reynolds Number

v_o = Velocity in flight direction

C_L = Total lift coefficient, $C_{L_p} + C_{L_v}$

α = Angle of attack

K_p = Constant in potential flow lift equation = $\pi A/2E$

K_v = Constant in vortex — lift equation = $\pi\sqrt{[16-(A\beta)^2][A^2+16]}/16E^2$

K_i = Induced drag parameter = $\delta C_{D_L}/\delta C_L^2$

Λ_{LE} = Sweep-back angle of leading edge from lateral axis

E = Elliptic integral of second kind where modulus = $\sqrt{1-(\beta\cot\Lambda_{LE})^2}$

β = $\sqrt{M^2-1}$

Λ_{C_D} = Drag due to lift coefficient $(C_D - C_{D_o})$

C_D = Drag coefficient

C_{D_o} = Drag coefficient at zero lift

V_T = Tangential component of speed in vortex flow

V_R = Radial Tangential component of speed in vortex flow

V_A = Axial Tangential component of speed in vortex flow

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