The Physics of Flight: It's Newton not Bernoulli

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The Bernoulli explanation of flight that we were taught is at best incomplete and often very misleading. A wing develops lift by diverting air down. Lots of air! This can be understood by simple Newtonian mechanics. With a few simple assumptions most phenomena associated with flight can be calculated to a good order without ever considering the details of wing shape, or invoking Bernoulli's Principle. Topics to be covered are: lift on a wing, inverted flight, the power curve, drag, ground effect, wing tip vortices, and more.

Tevatron University
Fermilab
Thursday, March 26, 1998

Hump Theory

("Stop Abusing Bernoulli. How Airplanes Really Fly")
(Gale M. Craig, ISBN 0-9646806-2-9)

What is taught may be called ***Hump Theory*** which is based on the ***Bernoulli theorem***, according to which pressure and velocity are inversely related, and on a ***principle of equal transit times***, which states that air going over and under a wing arrives at the trailing edge at the same time. You know the rest.

Take a Cessna 150:	Weight:	1600 pounds
	Wing area:	160 sq. feet
	Slow speed flight	55 mph

Upper surface path longer **1.6%** greater than the lower.

Lift at 55 mph according to Hump Theory: 40 pounds!

Minimum flying speed: >300 mph!

Hump Theory says that the upper path for the Cessna 150 must be 30% longer than the lower:

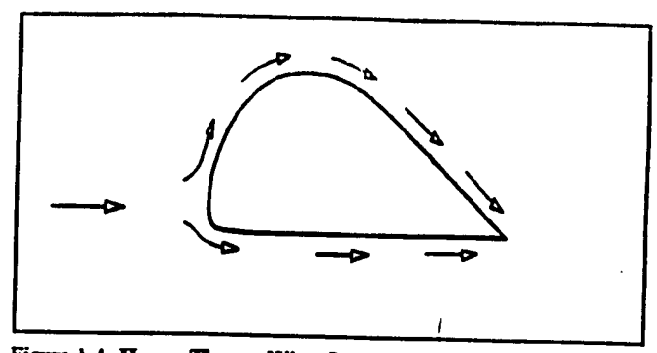


Figure 1.4 Hump Theory Wing Section for a Cessna 150

A Closer Look at the Standard Description of Lift

First the ***principle of equal transit times*** is not true. In fact the air passing over the wing arrives at the trailing edge first.

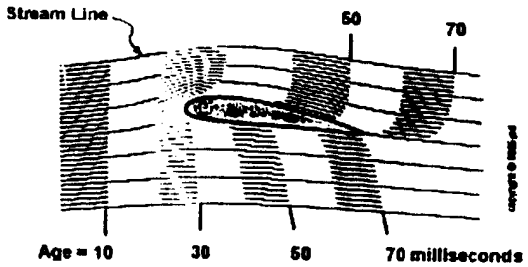
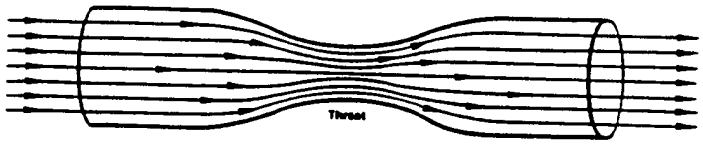


Figure 3.1 - Flow Past a Wing

(See How it Flies by John S. Denker)
(http://www.monmouth.com/~jsd/how/)

The standard explanation includes the description of a venturi, where the higher velocity yields lower pressure by Bernoulli's Principle.



What is Wrong With That Picture?

- If you drilled a hole in the venturi it would draw in air. The wing is not in a close pipe like the venturi.
- Why the undisturbed air above the vacuum does not get sucked into the vacuum like the wing.
- The explanation implies that lift is a surface (thin) effect.

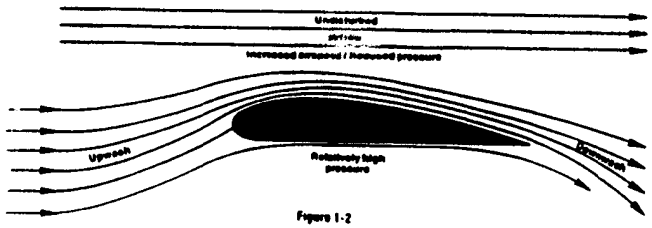


Figure 1-2

The Bernoulli explanation (as taught) does not explain:

- Symmetric wings
- Inverted flight
- Why lift requires power
- Upwash
- Ground effect
- How a wing can adapt to loads of -2g to +10g.

It's Newton not Bernoulli

A jet engine (or p ller) produces thrust by blowing air back.

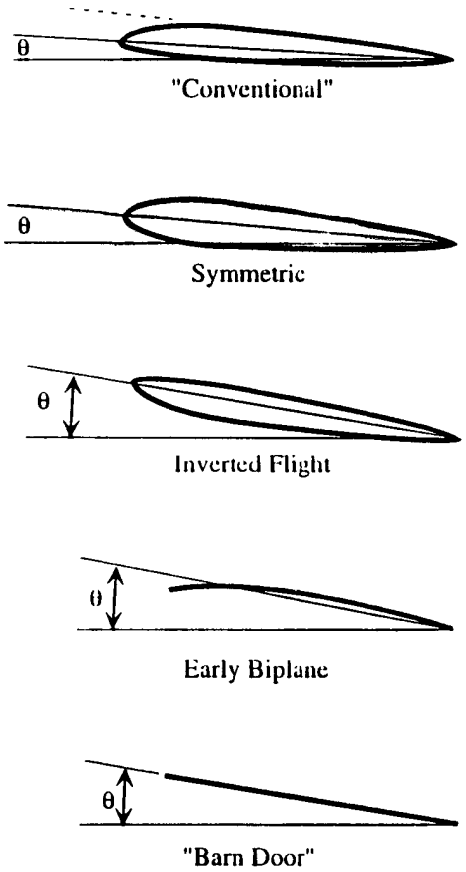
A helicopter (or a ble bee) hovers by blowing air down.

A wing p duces lift by diverting air down. Lots of air!

The lift is proport l to the **amount** and the **velocity** of air diverted down.

- If a plane were y low over a very large scale, the scale would weigh the plane. The eart es not get lighter when a plane takes off.
- If the driver of ck loaded with 500 pounds of canaries, sitting on a scale, were to fire a g o get them in the air, the truck would not get lighter.

Some Types of Wings



What all these wings have in common is an ANGLE OF ATTACK, θ.

Newton's Three Laws

Newton's first law

A body at rest will remain at rest, or a body in motion will continue in straight line motion unless subjected to an external applied force.

Newton's second law

When subjected to an external force the body will accelerate at a rate equal to the applied force divided by the mass of the body.

This is often written: $F=ma$

We will use a different form $F=\left\{\frac{m}{t}\right\}v$

This second form is often used to describe the thrust of a rocket (or jet engine) where $\left\{\frac{m}{t}\right\}$ is the mass per unit time in such units as kg/s and v is the velocity of the gas being discharged.

Newton's third law

To every action there is an equal and opposite reaction.

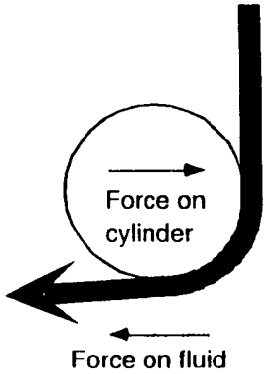
or

When two bodies exert mutual forces on one another, the two forces are always equal in magnitude and opposite in direction.

Key Concept: Why A Stream of Fluid Bends Around a Cylinder

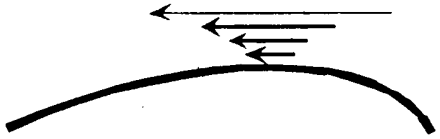
A thin stream of water from a faucet will wrap around a glass brought just close enough to touch it.

There is the same effect with a jet of air over a cylinder, or a wing



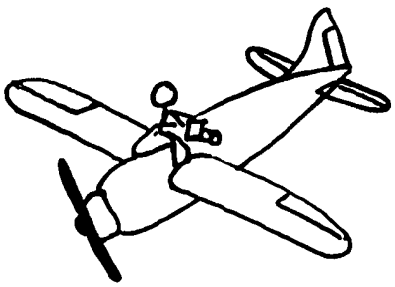
The key to understand is **viscosity**.

- The relative velocity (with respect to the solid surface) of the fluid is exactly zero for the layer in direct contact with the surface. **
- The speed of the layers increase with distance from the surface.
- Because of viscosity the layers of different speeds put a shear force on the fluid.
- The fluid bends around the surface without separating for "reasonable" bends.

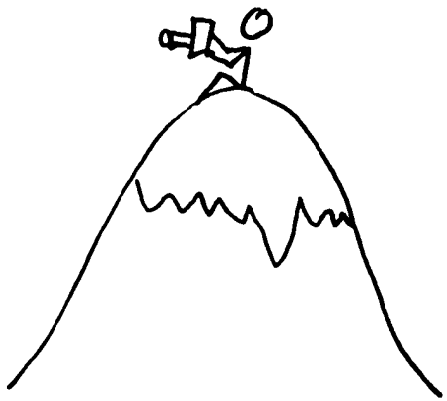


**This is why you cannot hose dust off your car, and why there is dust on the back side of the blades in wind tunnels.

Rest Frames



Wing Rest Frame
(Wind Tunnel)
wing stationary, air moves



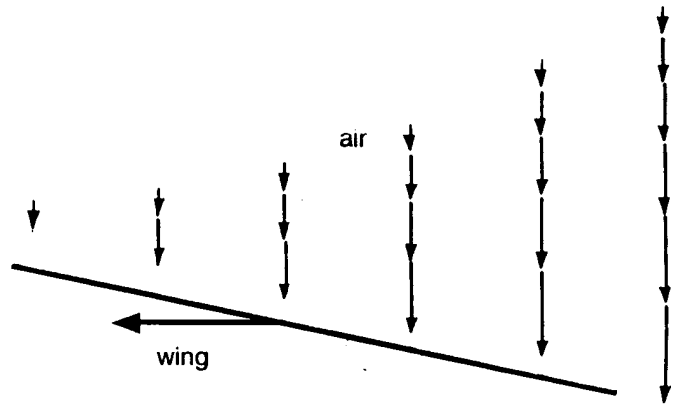
Lab Rest Frame
air stationary, wing moves

Downwash

A wing produces lift by diverting air down. Lots of air!

The Wing as a Pump(in the lab rest frame)

In the lab rest frame, the air sees a receding surface like that of a pump. At the last minute the wing gets out of the way and the air goes straight down.



The air is accelerated down, by the low pressure on top of the wing, which requires a force.

By Newton's third law an equal and opposite force is exerted on the wing.

The fact that the air goes mostly straight down can be seen in the air of a household fan or the propeller on a plane.

- The air comes off in a in a tight, well defined cylinder.
- If the air did not come off the blades vertically (in the lab rest frame) the air would sweep a cone.

The Wing as a Pump(in the wing rest frame)

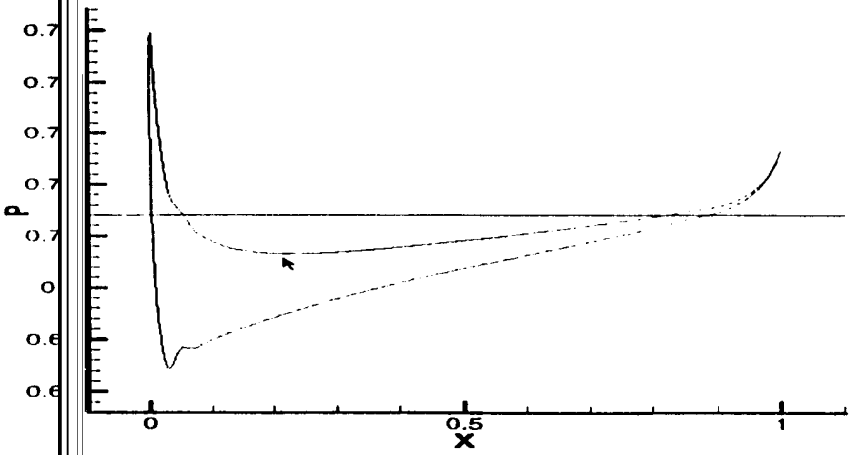
The air bent around the wing exerting a force on the wing and lowering the pressure

This lowered pressure also accelerates the air over the top of the wing.

The air above the wing tries to fill the vacuum from above.

As before, a large mass of air is accelerated downwards.

Any point that the air bends the air exerts a force on the wing.



Pressure on a symmetric wing with a 2° angle of attack. The curve marked with an arrow is the lower surface. The horizontal line is the ambient pressure.

The pressure difference is greatest on the front of the wing (where the wing curvature is greatest) and decreases along the cord.

The velocity of the air diverted down (and therefore the lift) is proportional to the angle of attack.

The angle of attack Is more important than the details of the wing shape.

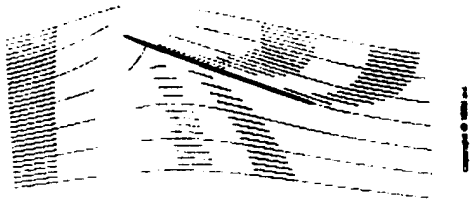
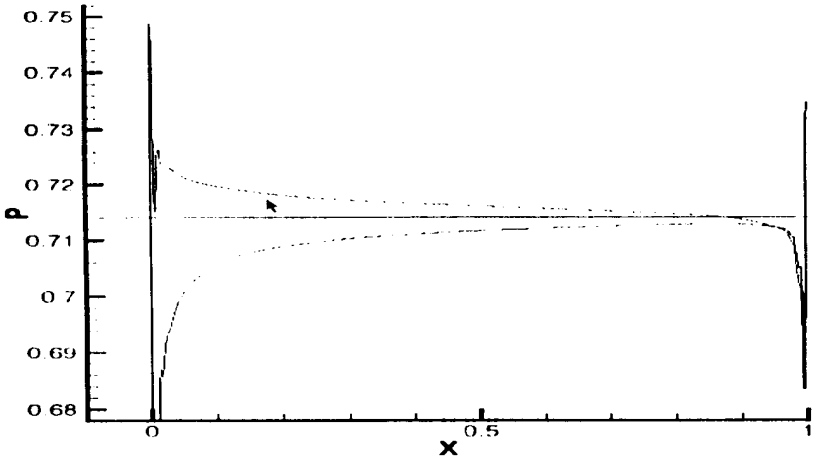


Figure 3.15 - Barn Door: Natural Airflow

(How it Flies by John S. Denker)
(http://www.monmouth.com/~jsd/how/)



Pressure on a "Barn Door" with a 2° angle of attack. The curve marked with an arrow is the lower surface. The horizontal line is the ambient pressure.

In inverted flight the angle of attack compensates for the non-ideal shape of the wing.

Power Requirement of Lift
(Where is the work done)

Induced Power, P_i

We have shown that the lift on a wing is given by

$$F = \left\{\frac{m}{t}\right\} Vv, \leftarrow$$
$$= \text{weight}$$

The work per second is proportional to

$$E \approx m \cdot Vv^2$$

(note: ≈ "means proportional to")

The induced(due to lift) power associate with lift is

$$P_i \approx E/t$$

$$P_i \approx \left\{\frac{m}{t}\right\} Vv^2 \leftarrow$$

For a fixed load

$$P_i \approx F\,Vv \leftarrow$$

Induced Drag, D_i

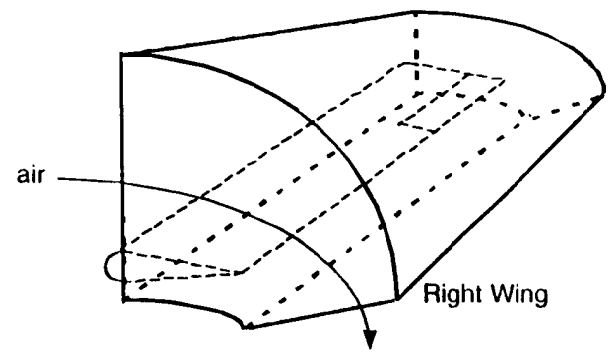
Drag is a force.

Power is force times speed.

$$D_i = P_i/\text{speed}$$

The (Induced) Power Curve

Again look at the wing as an air scoop



Assume that the size of the scoop is fixed (defined by the length of the wing and with a height related to the chord length by the speed of sound).

Thus $\left\{\frac{m}{t}\right\}$ is proportional to speed and air density, ρ.

Since weight $= \left\{\frac{m}{t}\right\} Vv$, and $\left\{\frac{m}{t}\right\} \approx$ speed and ρ

$Vv \approx 1/\text{speed}$ and $1/\rho$ (since $\left\{\frac{m}{t}\right\} Vv$ is a constant)

$Vv \approx$ angle of attack

As speed ↑, $\left\{\frac{m}{t}\right\}$↑, and thus Vv ↓. and the angle of attack ↓

Since $P_i \approx \text{load} \cdot Vv$ (for a fixed load)

$$P_i \approx 1/\text{speed}$$

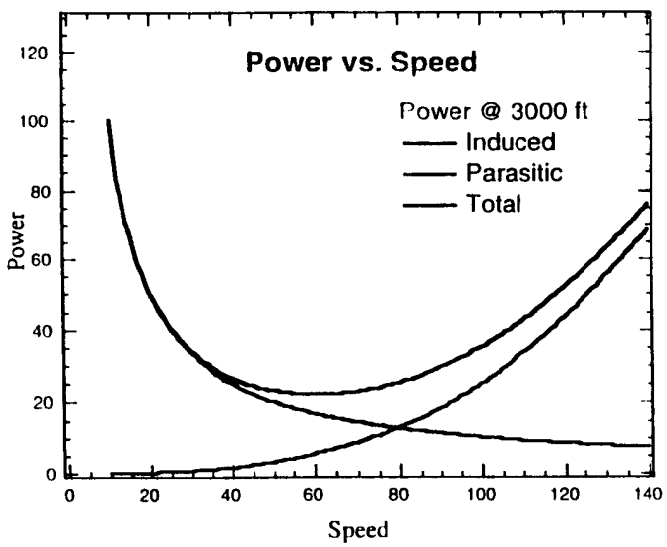
The (Parasitic) Power Curve

The energy imparted to an air molecule when hit by an antenna or strut is proportional to the speed^2. ($E=1/2\ m\ v^2$)

The number of molecules impacted per second is proportional to the speed.

Therefore, $P_p \approx \text{speed}^3$

Induced, parasitic, and total power curves as a function of speed



The total power goes as

$P_t \approx A/\text{speed} + B \cdot \text{speed}^3$, where A and B are constants.

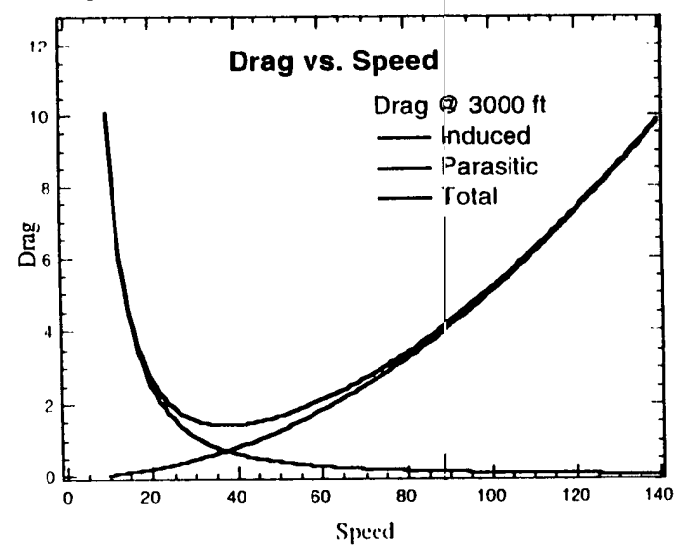
The Drag Curve

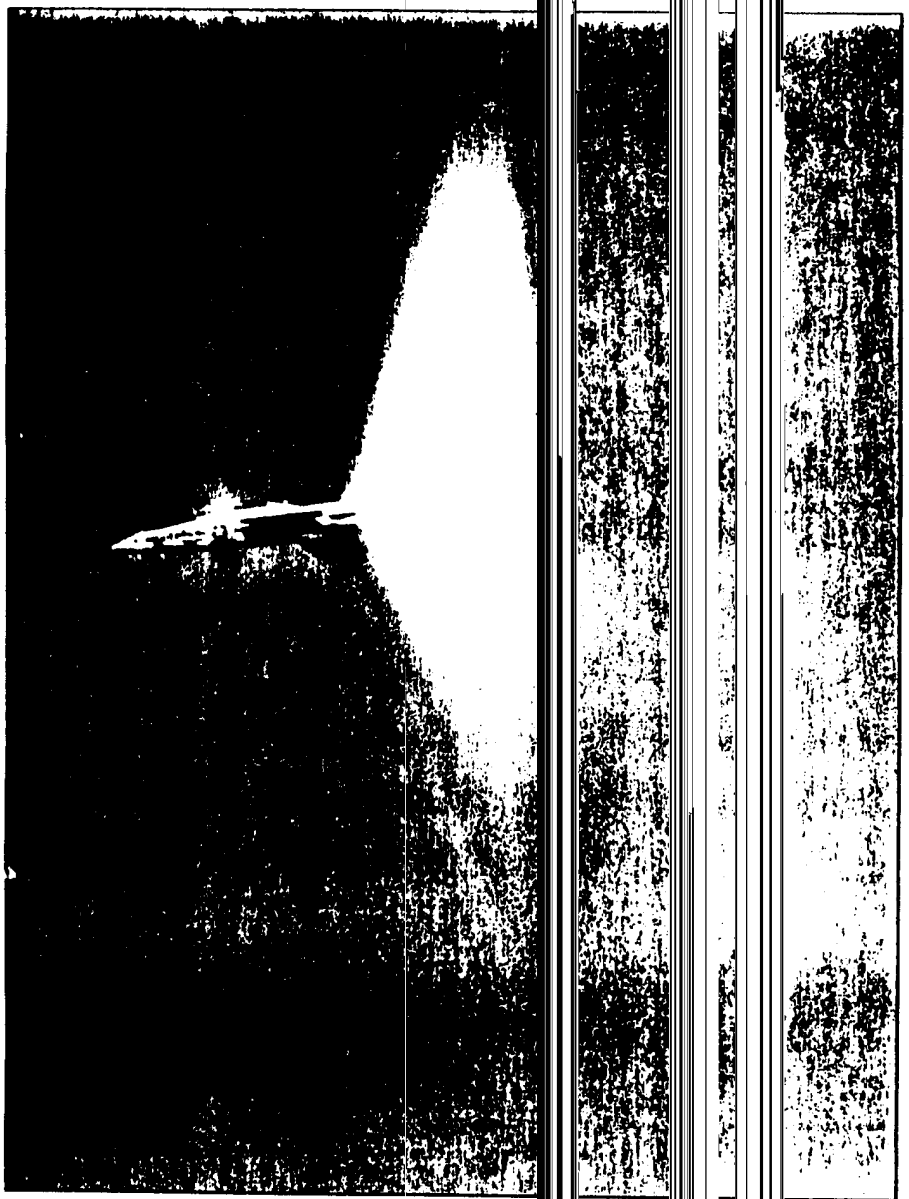
Drag = power / speed

and $D_i \approx P_i/\text{speed} \approx 1/\text{speed}^2$
and $D_p \approx P_p/\text{speed} \approx \text{speed}^2$

Thus $D_t \approx A/\text{speed}^2 + B \cdot \text{speed}^2$

Induced, parasitic, and total drag curves as a function of speed

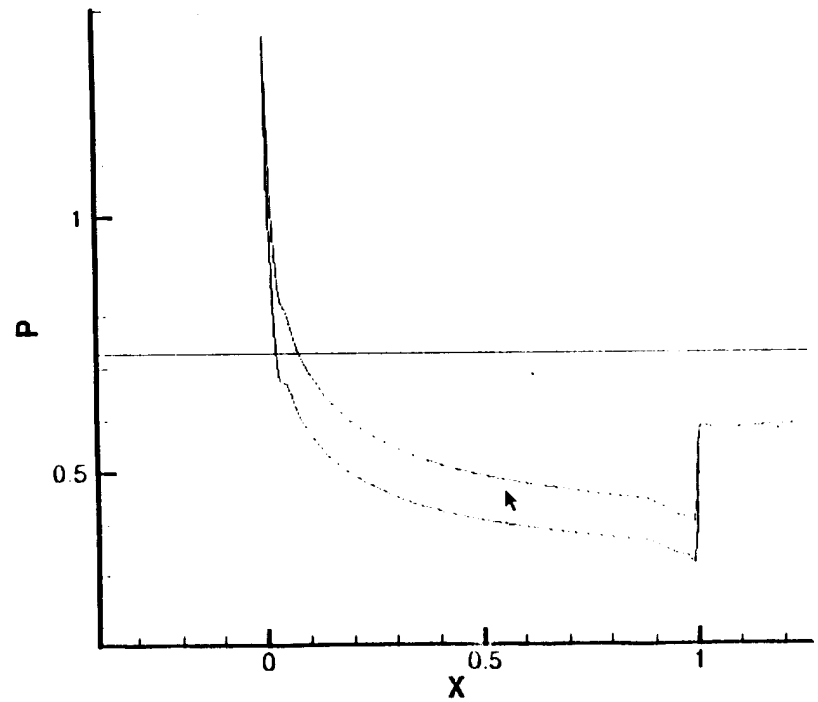




Expansions and shock patterns on F-14A in level flight at M = 0.9 with full-aft sweep.

Pressure Distribution of Symmetric Wing at Mach-1

2° angle of attack



The arrow points to the pressure on the lower surface.

The horizontal line is the ambient pressure.

How much air is accelerated downwards?

An example: a Cessna 172

Weight:	2300 lb.
Speed:	120 knots
Assume:	average vertical velocity of the air, Vv, is 9 knots

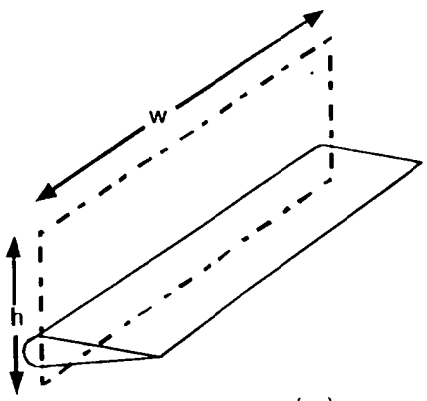
From Newton's second law; $F=\left\{\frac{m}{t}\right\}Vv$

$$\left\{\frac{m}{t}\right\} \approx \mathbf{5000\ lb./s\ !!}$$

This is a lot of air and is not just a surface effect.

Remember: a cubic yard of air at sea level weighs about 2 lb.

How big is the "scoop" intercepting the air?



$$\left\{\frac{m}{t}\right\} = w \bullet h \bullet \text{speed} \bullet \text{density}$$

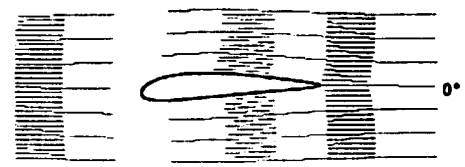
For the Cessna 172 above at 3000 ft with w=36 ft.

$$h_{average} \approx \mathbf{9\ ft\ !!}$$

As will be discussed later, these numbers my be a factor of 2 too small because of upwash.

Angle of Attack: How the Wing Adjusts to Insure F = Load.

If one defines the angle of attack to be zero when lift equals zero:



(How it Flies by John S. Denker)
(http://www.monmouth.com/~jsd/how/)

Than the lift is a linear function of the angle of attack with zero lift at zero angle of attack:

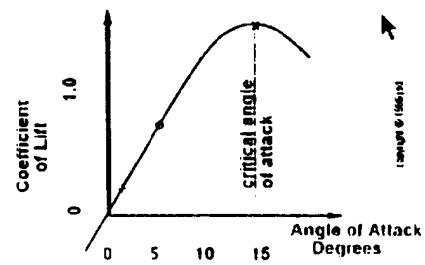


Figure 2.14 - Coefficient of Lift versus Angle of Attack

(How it Flies by John S. Denker)
(http://www.monmouth.com/~jsd/how/)

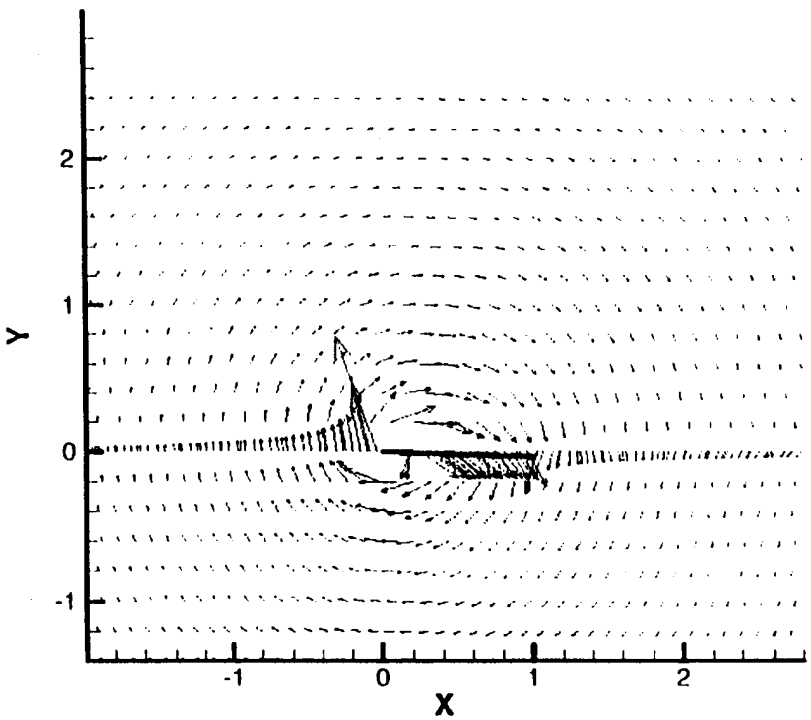
The lift vs. angle of attack curve has the same slope for almost all wings!

All wings (747 to a barn door) have similar curves that are linear for angles of attack away from stall.

In understanding flight, understanding the role of the angle of attack is much more important than the details of the shape of a wing.

Flat Plate (Barn Door)
Seen in the Lab Rest Frame

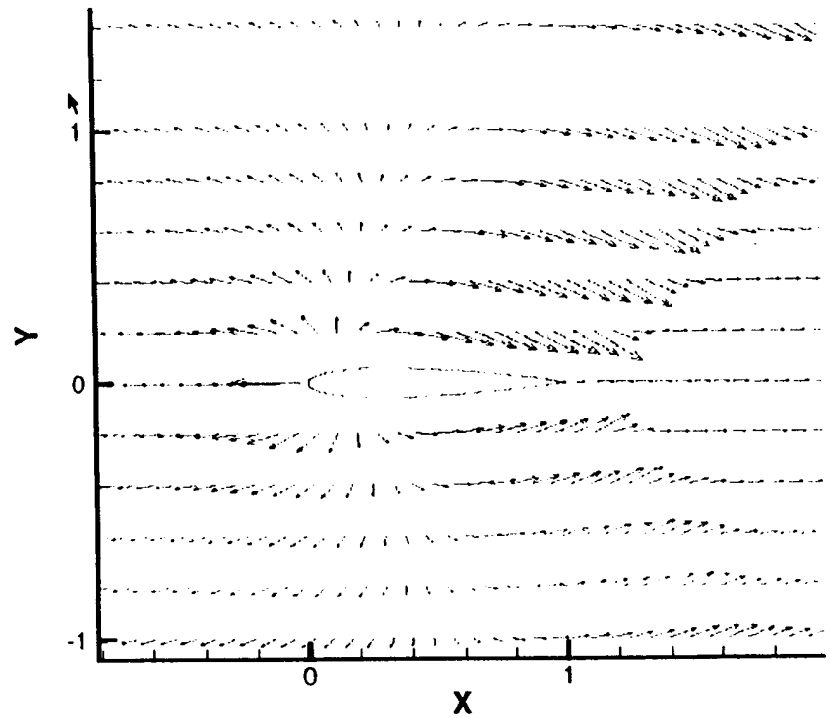
:° angle of attack



Remember: The air only <u>appears</u> to go around the wing.

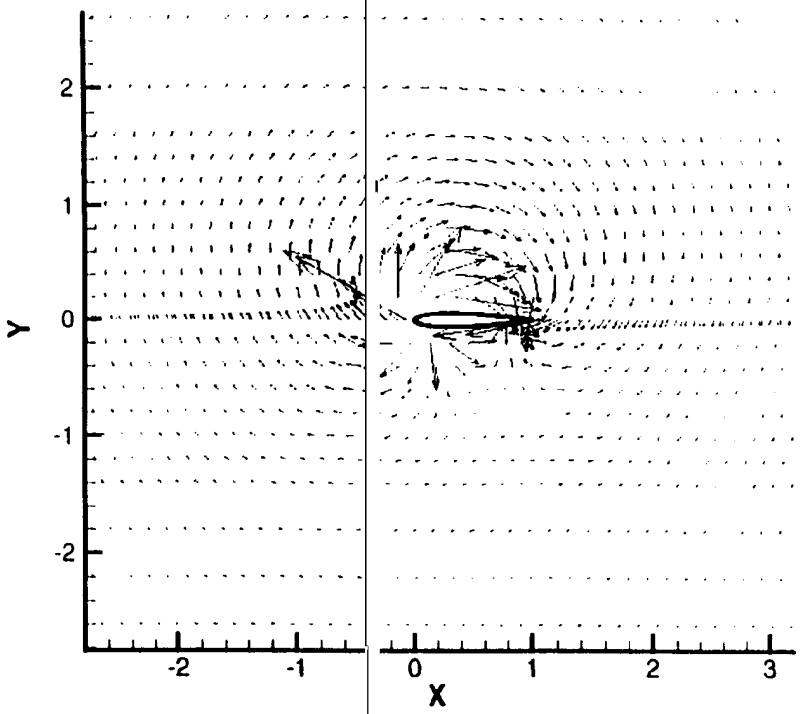
Symmetric Wing at Mach-1
Seen in the Lab Rest Frame

2° angle of attack



Symmetric Wing Seen in the Lab Rest Frame

2° angle of attack

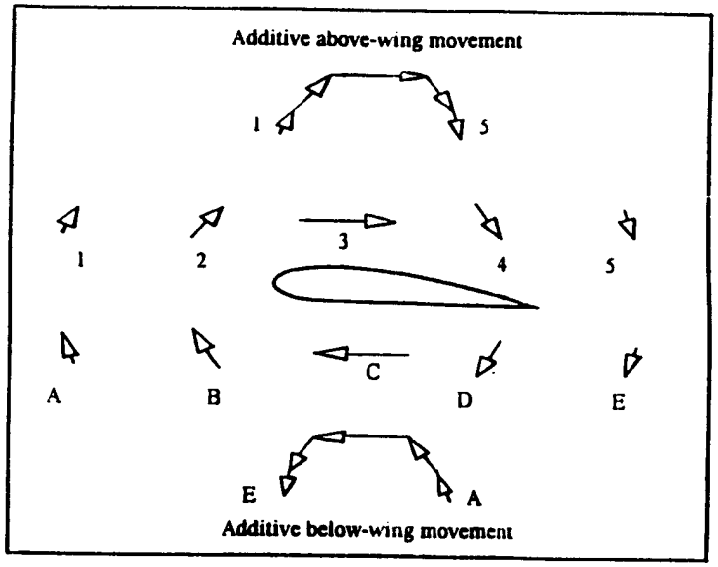


The wing is seen to be moving and the air, before the arrival of the wing, is standing still.

Circulation

For the sake of understanding airflow around a wing, air must be viewed as a viscous, incompressible fluid.

- The wing moves air back (mostly over the top) and down.
- To replace this air, air moves forward (mostly under the bottom) and up. **This is the source of upwash.**
- **The return air is not the same air that went over and down.**



Integrated Downwash Increments
(Stop Abusing Bernoulli-G. Craig)

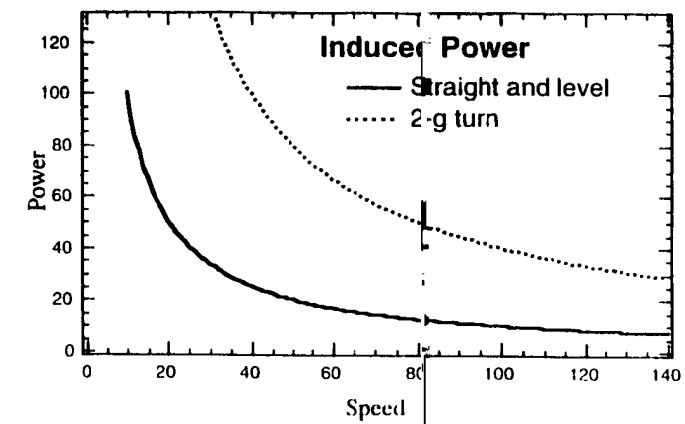
A snapshot of the air movement in the lab rest frame appears that the air is going around the wing. By adding the vectors sequentially, one see that the motion as the wing passes is convex upward, both above and below the wing.

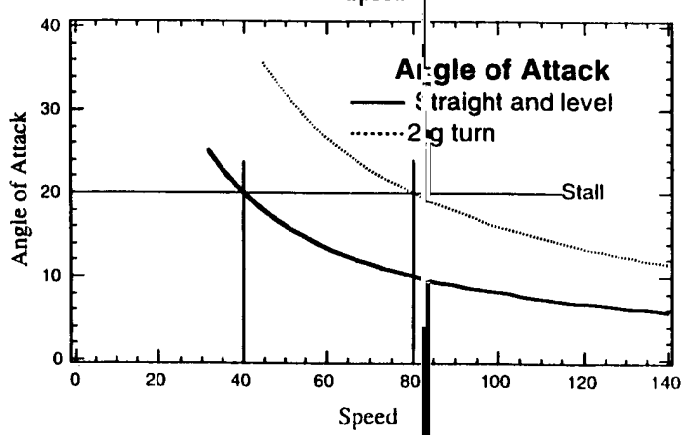
The acceleration of the air is down and thus force is up.

Effect loading on Power

Since $\left\{\frac{m}{t}\right\}$ is constant for a constant speed and altitude, an increase in load (weight) requires and increase in Vv (and an increase in angle of attack).

As F (weight) ↑, Vv (and angle of attack) ↑, and P_i ↑ as Vv^2.





This clearly shows the effect of loading on stall speed.

Wi Efficiency

A wing itself has very little parasi rag.

The D_p of the wing of a 747 is th ne as for a 1/2 inch cable of the same length.

The power requirement for the w s primarily P_i.

Lets define wing efficiency as

Efficiency = lif

Efficiency as a fu n of wing and chord length

As the length of the wing, L, ↑ {

As the chord length of the wing, ↑ $\left\{\frac{m}{t}\right\}$↑, but not linearly.

$\left\{\frac{m}{t}\right\}$ ≈L, and i ses with Lc

For the same lift

Vv ≈ 1/L

For a constant lift (load)

P_i ≈ 1/L, wher s the wing length

and

Efficiency ≈ L increases with chord length, Lc.

Wing Efficiency

a constant lift | oad
≈ 1 | here L is the wing length
ffici | ≈ L** and increases with chord length, Lc.

This explains | ny g | s are very efficient, helicopters are less efficient than
fixed-wing | craf | cted-fan engines are more efficient than conventional
jet engines, | nd y | n't hang on you propeller.

oblem often s | n in | literature: "Lift does not require work".
e reason for th | mis | standing is that aeronautical engineers find it easier
do calculation | or w | of infinite length (or 2-D sections which are
tions of infini | win | nd as $L \to \infty$, $P_i \to 0$!

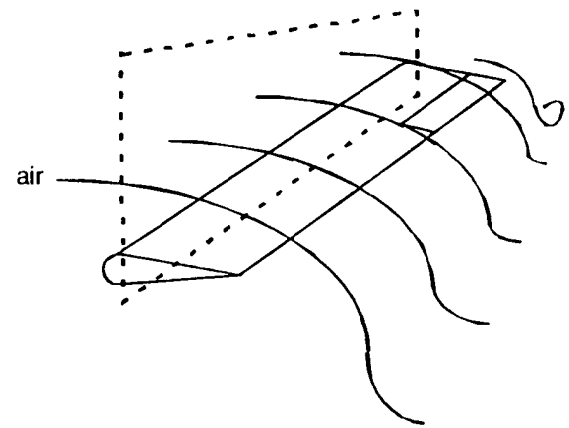
ift did not re | ire | er:

- **Planes | uld | the same range as empty or full.**
- **Helicop | s c | hover at any altitude and load.**
- **Propul | n w | not require power either (same physics).**

Wing (Tip) Vortices

The lift of a wing decreases with distance from the root.

Thus the downwash velocity decreases with distance from the root



Like the curvature of the air over the wing, the change in downwash velocity along the wing causes it to make a slow curl towards the end of the wing.

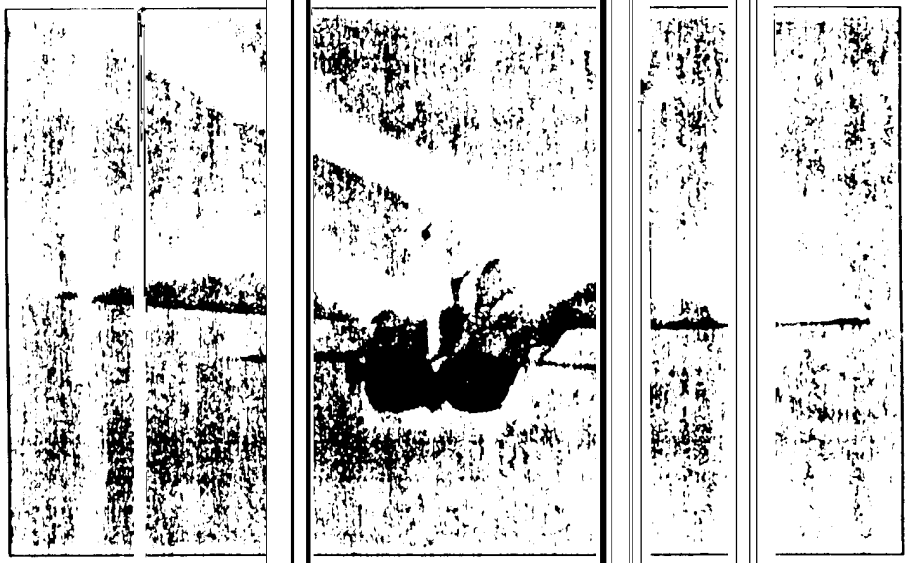
This is the wing vortex and is made up of the curl of the downwash sheet.

The tightness of the curl is related to the rate of change of velocity with position.

At the end of the wing there is a discontinuity and the curl is very tight.

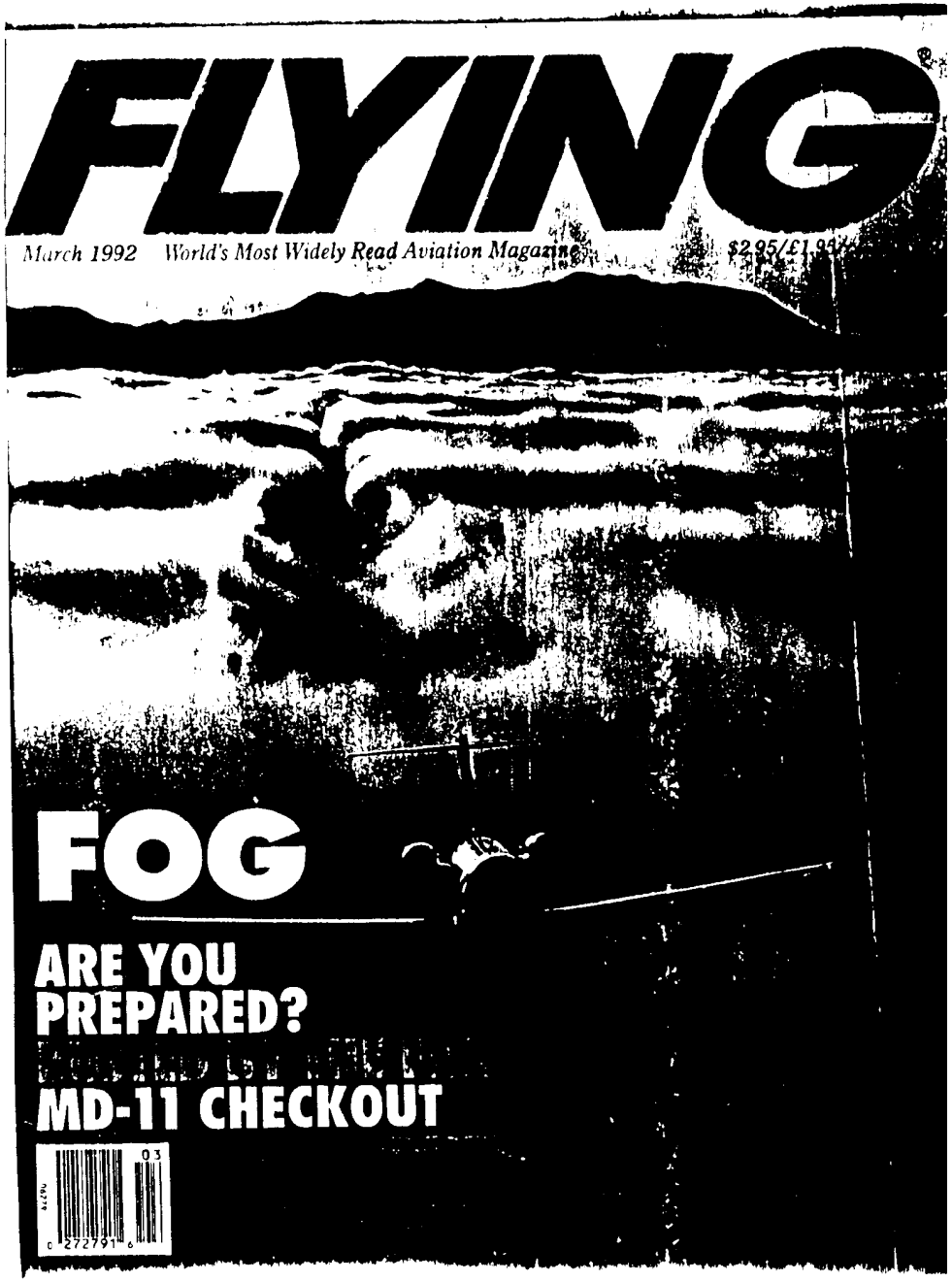
This is the wingtip vortex

Problem often seen in the literature: "Induced drag is due to the wing tip vortices."
Since the calculations with an infinite(or 2-D) wing yield lift without power, the drag has to be put in somewhere. As we have seen the induced power (and induced drag) are due to the energy put into the downwash sheet to give lift. So, there is no problem with a statement that the induced drag is due to the wing vortices. The wing tip vortex, though a small part, is proportional to the total vortex.



Gull pattern and w gtip vortices create ACT airplane during 3.3g maneuver. M = 6.9° win 26 3 • 1

Gull pattern of cal lated relative hum or Boeing 747. M = 0.84; α = 2.4° 3 • 2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Ground Effect

following descripti is an adaptation, from the standpoint of this talk, of
of the excellent exp ıation of ground effect by Barry Schiff (The Proficient
ıt, A.O.P.A, 1980).

ıund effect is the red tion in induced drag and induced power when the
ıe is within a wings ıgth of the ground.

ample: Cessna Ca inal with 36 ft wingspan

ng height in feet	% of wing span	% reduction in D_i
	00	2
	50	8
	25	2
(not possible)	3	50

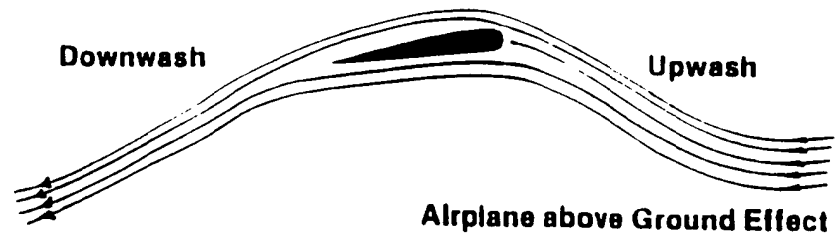
any pilots (and FA /FR Exam-O-Gram No. 47) mistakenly believe that
ıund effect is the r ılts of air being compressed between the wing and
: ground.

Understanding Ground Effect

The explanation of ground effect is quite simple.

Because of circulation, discussed earlier, The wing has a significant upwash which transfers momentum in the wrong direction.

Thus the wing must have more downwash (and thus P_i and D_i) to compensate for it.



Barry Schiff (The Proficient Pilot, A.O.P.A, 1980)

The proximity of the ground interferes with the circulation under the wing and thus reduces the upwash.

Barry Schiff (The Proficient Pilot, A.O.P.A, 1980)

Reduced upwash means a reduction in needed downwash (and thus P_i and D_i) and a smaller angle of attack.

One Last L
Bernoulli or N on

Consider the wing of the Wright Flyer:

Wright Flyer Wi

Bernoulli: A computer simulation would sh at the air passing over the wing (outside curve) is accelerated and the ai sing under the wing (inside curve) is retarded. Since the Bernoulli equat lates velocity to pressure the lift can be calculated. **(Non-Intuitive)**

The problem with the Bernoulli e ination is that it fixates on the shape of the win The description leaves one without the tools to unders l such fundamental phenomena as the adjustment f rge load changes or where the work is done.

Newton: The air above and below the wing w the wing shape. Since the air is bent down (momentum transfer) there is a up. **(Intuitive)**

The Newtonian approach focuse n the angle of attack. The lift increases linearly with a of attack until the stall condition is approached. This describes wings from a 74 a barn door.