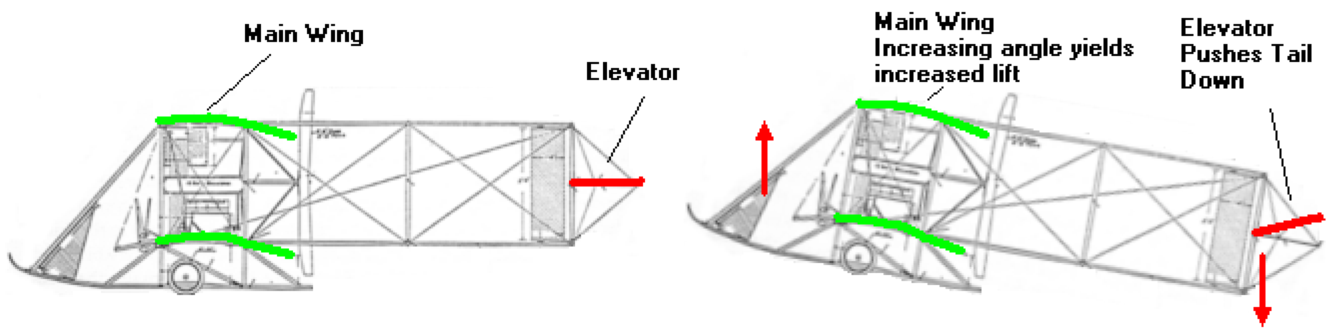
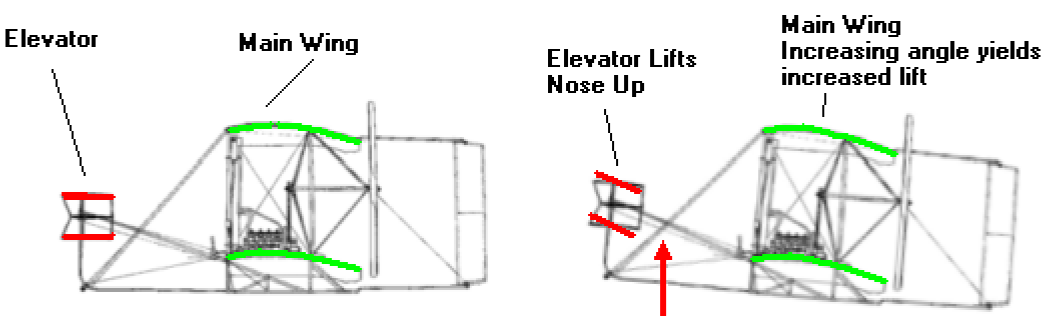
The Wright Flyers and The "Undulation" Problem

The undulation problem was a problem that hindered the Wright Brothers in their quest for controlled flight. It was a particularly pressing problem in the years 1903 through 1905. In part the problem was the result of the brother's choice of placing the "horizontal rudder", now known as the elevator, in front of the main wing. Most plane designs before the Wrights and after the Wrights place the elevator behind the main wing. To understand their reason for choosing this configuration you need to understand a little about the tradeoffs involved. The Wrights were working in a world of limited power for their flying machines and much of their designs were about obtaining maximum efficiency. They did all those wind tunnel test to create a method of wing design which allowed them to design a wing on paper, build it, and then get very nearly the results they expected. They developed the theory of how to design air propellers and used this theory to design the most efficient propellers of their time. This attention to detail and efficient design is what made them successful where others had failed. Orville Wright presented a lecture on the "Stability of Airplanes" at the Franklin Institute in May of 1914. In this lecture he pointed out the adverse power requirements of the, now standard, elevator in the rear configuration and the lesser power requirements of the elevator in front configuration, now called a canard. His main point was that it takes more thrust to go up if you do it by pushing down. If the elevator is in the rear as shown here

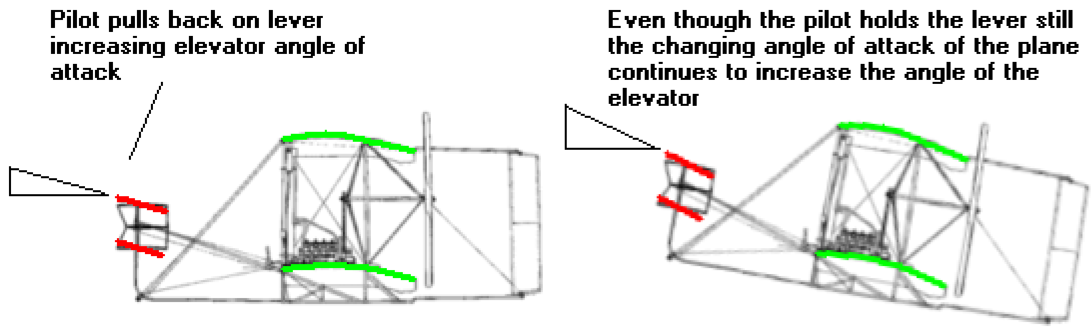


the plane is made to climb by reducing the angle of attack on the elevator, usually to a negative angle, thereby reducing the lift or actually pushing down on the tail of the plane to pitch the main wing to a more positive angle of attack. The more positive angle of attack on the main wing creates more lift and causes the plane to rise. Every pound of lift (up or down) requires about 1/6 pound of thrust. If you push down on the elevator with a pound of force you have to counter that with a pound of lift on the main wing. The result is the requirement of 1/3 pound of thrust per pound of pitch force and no net lift from the elevator . If you use an elevator in front configuration as seen here



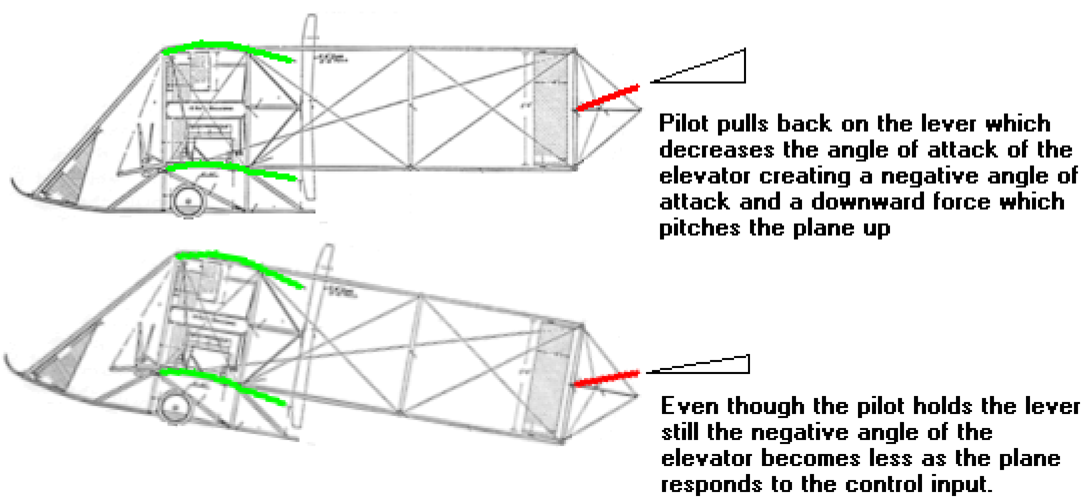
you increase the angle of attack of the elevator to increase the lift on the elevator which lifts the front of the plane and pitches the main wing to a higher angle of attack also increasing its lift. So for one pound of upward pitch force you need 1/6 pound of thrust. Half the requirement of the rear elevator configuration. And in addition you actually added a pound of lift to the plane. So if you want to build an airplane that requires a minimum of thrust consider using a front elevator configuration. And thats just what the Wright Brothers did. But this came with a cost.

The front elevator configuration is inherently unstable. To understand this look at the drawing here.



To go up the angle of attack of the front elevator is increased. The front of the airplane goes up. This pitches the main wing to a higher angle of attack increasing its lift causing the plane to rise. But at the same time, because the elevator is connected to the main wing, the elevator's angle of attack is furthur increased by the amount the main wing angle of attack increases. This in turn increases the lift on the elevator pitching the main wing to an even higher angle of attack. So the pitching force from the elevator increases as the plane responds to the control input even though the pilot is holding the elevator in the same position. In control theory this is called **positive feedback**. If uncountered it could cause the plane to pitch up to the point where either the elevator stalls or the main wing stalls or both. So the pilot has to rapidly move the elevator to a lower angle of attack to counter this. The pilot must stay ahead of the self amplifying control response.

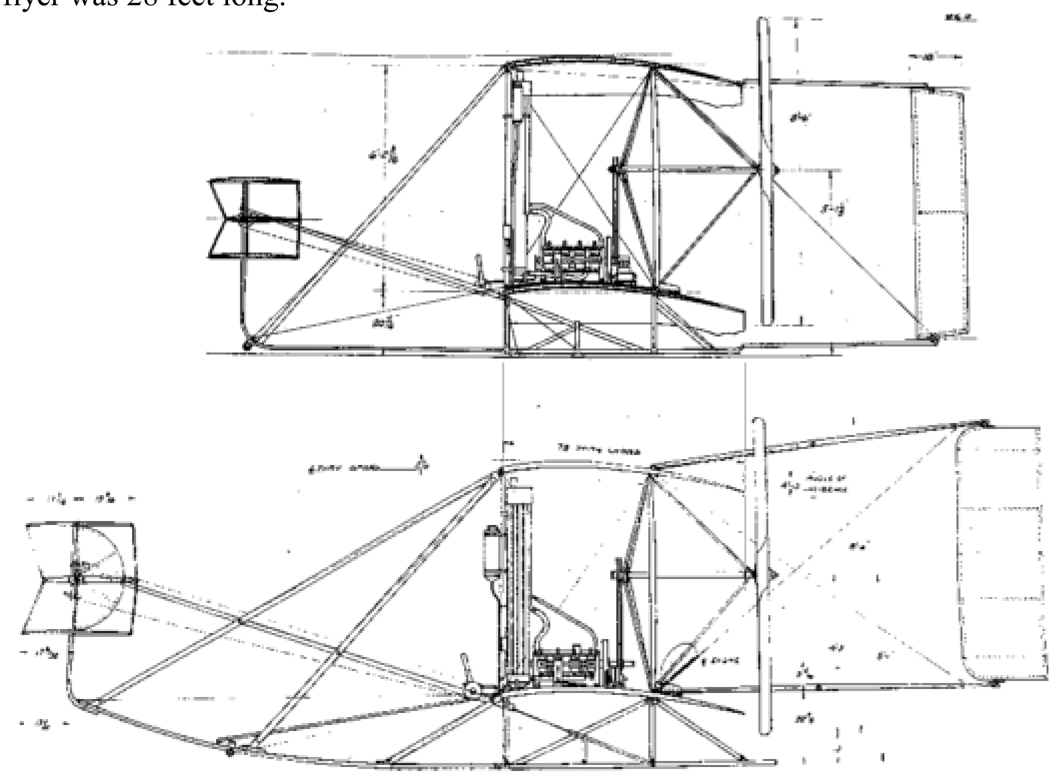
The rear mounted elevator doesn't have this particular problem. Look at this drawing.



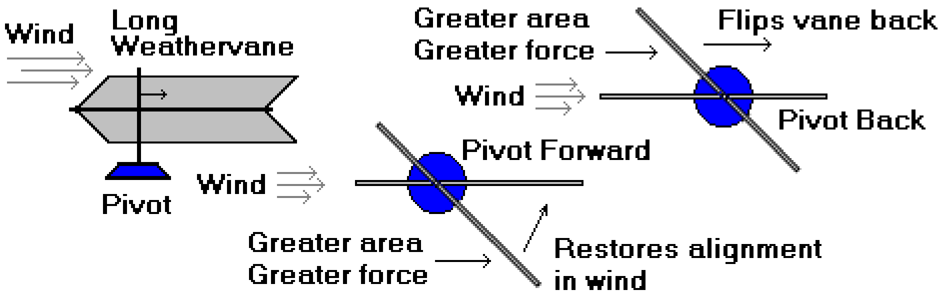
To go up the angle of attack of the elevator is decreased. Actually moved to a negative angle of attack. The tail goes down and the main wing pitches to a higher angle of attack and the plane goes up. But what happens to the elevator's angle of attack here. The elevator rotates with the plane and the main wing and its negative angle of attack actually becomes less. The pitching force from the elevator drops off as the plane responds to the control input. This is called **negative feedback**. It is inherently more stable. So the plane is easier for the pilot to fly.

The Wrights experienced the "undulation problem" particularly strongly with the 1903 flyer. The pitch instability caused them to have to constantly work the elevator control lever to keep the plane from stalling or hitting the ground. It was constantly going up and down. Their initial thought was that the front horizontal rudder was "overbalanced". This means the point where they pivoted the front rudder was behind the point where the air flow balanced on the surface. The air flow would tend to flip the control surface back increasing the response of the surface to movements. But after making changes they still had the undulation problem. They also thought they could learn to compensate for the problem with more piloting experience. Just more practice. But they couldn't tame the bucking machine in flights at Huffman Prairie through 1904. They began experiments to see if changes to the plane could improve the flyability of it. They shifted the engine position and played with a 70 pound weight to see if moving the center of gravity backward or forward would help solve the problem. They tried a slightly different camber on the wing. The 1905 flyer started off no better. After a particularly bad crash on July 14, 1905, that Orville was lucky to escape uninjured, they did major changes to the airplane. They increased the height of the structure on the bottom of the flyer to raise the plane and pilot higher off the ground. They increased the length of the front structure moving the elevator 4 feet farther from the main wing and improving the shape of the runner area for landing in the grassy field. This provided a better structure to support the aircraft during landings and also protect the pilot. They also increased the length of the rear vertical rudder structure and enlarged both the front horizontal rudder (elevator) and the rear vertical rudder. They had decided they needed more available force from the control surfaces and the length increase and surface area increases accomplished that. The center of gravity was moved forward on the main wing.

A comparison of the 1903 and late 1905 Wright Flyers. The 1903 flyer was around 21 feet long and the 1905 flyer was 28 feet long.

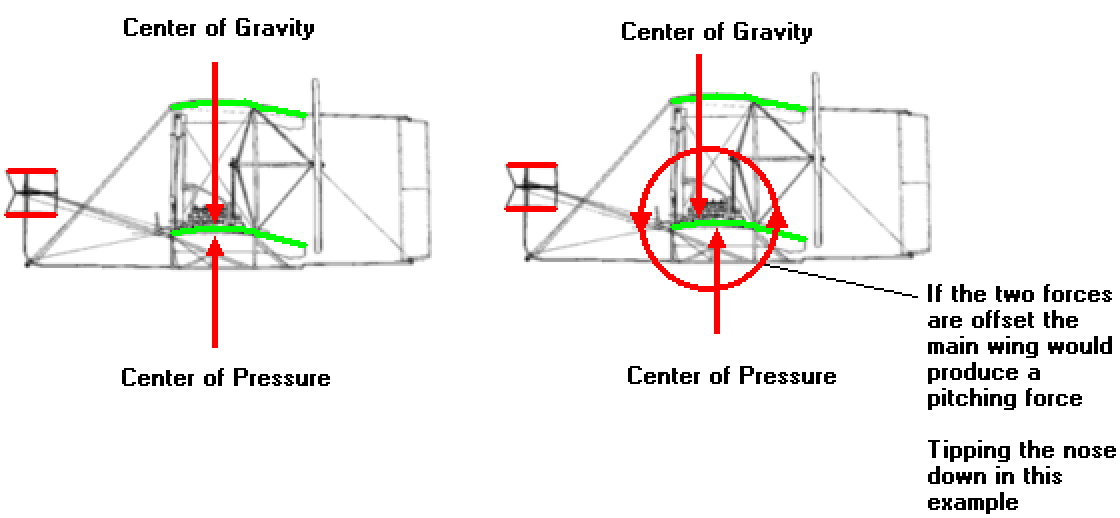


Increasing the length of the plane has mixed results. The 1903 through early 1905 planes were around 21 feet long. The late 1905 plane was 28 feet long. Its just a matter of physics and geometry that a longer plane will have a lower pitch rate. If you move mass farther from the axis of rotation it will be harder to produce rotation around that axis because for a given change in rotation rate you need to accelerate the mass more. So the plane would be more stable. But moving a larger surface further in front of the center of gravity actually adds to the instability. It undoes some of the gains in stability.



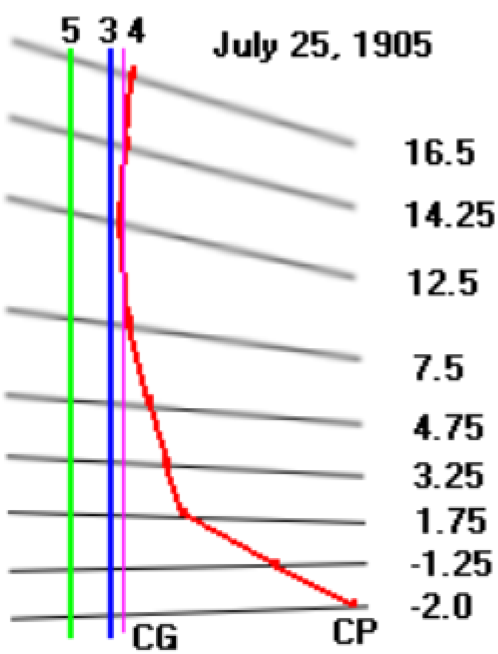
A way to understand the effect of the position of the center of gravity (CG) and the location and size of surfaces is to realize that the CG is the rotation axis or the pivot point of the airplane. Then compare an airplane to a weathervane with the weathervane tail the aero surfaces and the pivot point is the equivalent to the CG. As long as the tail is behind the pivot the weathervane is very stable. If the tail is pushed around in the air flow and released it quickly flips back to directly behind the pivot. For an airplane this would actually be too stable. If the tail is placed in front of the pivot in the airflow it flips around to behind the pivot. The tail behind the pivot is stable but the tail ahead of the pivot is not. The tail will not stay ahead of the pivot without someone holding it there. If you make a long "tail" thats most of the length of the weathervane and move the pivot fore and aft you can see the effect of moving an aircraft's CG forward and back. As the pivot moves forward more of the surface moves behind the pivot and the weathervane is more stable. But as the pivot moves backward more surface moves ahead of the pivot and the weathervane becomes less stable until it flips around.

The net effect of the air flowing around a wing results in a force which can be seen to be balanced at a particular point on the wing. This is the point at which there is no pitching force on the wing. The forces to the front are the same as the forces to the rear. The point is called the center of pressure. The center of pressure (CP) is actually a term from sailing. A boat in trim has its sails set so that the CP is at the center of rotation of the boat. For instance over the center board. In this situation the wind doesn't tend to turn the boat. This allows the rudder to be held straight in the water to keep the boat sailing straight and results in the least drag. If the boat wasn't in trim the boat would be turned by the wind and the rudder would have to be slightly turned to counter the wind force and keep the boat on course. That would add more drag and slow the boat. In an airplane the center of gravity is pretty much the center of rotation. The brothers felt it was important to have the center of gravity and the center of pressure to be close to the same point so that the main wing was in pitch balance. So when flying level the "horizontal rudder" could be held flat and have the minimum drag. This is the efficient choice.



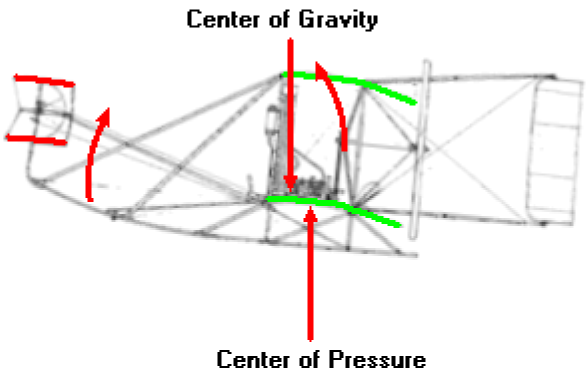
The 1903 flyer was designed so that the main wing was nearly in balance at their design angle of attack. Most information on the 1903 Wright Flyer indicates that the "front horizontal rudder" was non-load carrying which would fit with the sail boat rudder analogy. My calculations show that it may have carried about 9 percent of the weight at the normal flying angle but the Wrights own notes may support the non-load carrying situation. On several occassions the Wrights noted using more pressure on the top of the horizontal rudder than they felt was right. This indicates that the front horizontal rudder was actually pushing down on the front of the plane so the front rudder was acting both to push the front down and lift it up at different times. Its believed that the flyer was balanced with the plane's center of gravity at 29 percent of the cord back from the leading edge of the wing. The Wrights knew from their wind tunnel experiments that the center of pressure shifts with a changing angle of attack of the wing and that their cambered wing shape had an interesting way in which the point shifted. As the angle of attack increases the center of pressure moves forward. As the angle of attack decreases the center of pressure moves rearward and can move rapidly towards the trailing edge at low angles of attack. So the shift in center of pressure added to the pitch instability by varying the forces relative to the center of gravity. At high angles of attack the center of pressure of the main wing possibly passed the center of gravity. This added to the up pitching force. As the angle of attack decreases and moves negative the center of pressure moves rapidly towards the trailing edge. At -2 degrees it would be at 97% back on cord. This would generate more down pitching force.

This is my plot of the Wright brothers center of pressure (CP) data from July 25, 1905 when they were rebuilding and modifying the 1905 flyer.



The angled lines represent the angle of attack of the wing. The numbers are the actual angles from the Wrights data. The vertical lines represent the location of the center of gravity (CG) on the Wright flyers at various times (3) 1903, (4) 1904 when the engine was moved rearward, and (5) 1905 after the modifications. As you can see on the late 1905 flyer the CG was moved further ahead of the CP. The source of the CP versus angle of attack data that the Wrights used at this time is not known. They may have produced the data from their own wind tunnel test or they may have got the data from George Spratt who had collected center of pressure data from his own wind tunnel test. George Spratt originated the use of balances to measure the lift/drag of surfaces in a wind tunnel. The Wrights created their own versions for their wind tunnel testing.

The changes to the flyer in July and August of 1905 shifted the center of gravity forward to 18 percent back from the leading edge so that the main wing was less in pitch balance at its normal flying angle of attack. The shift in center of gravity kept the center of pressure behind the center of gravity even as the wing's angle of attack changes. By itself the main wing would pitch down. This shifted more weight to the elevator up front. Perhaps 12% of the weight was carried by the front horizontal rudder. Moving the center of gravity forward increased the distance between the CG and the CP. This made the airplane more stable and provided negative feedback to balance the positive feedback from the front mounted elevator.



The front horizontal rudder pitches up, it's lift increases and the whole airplane pitches up. The increased lift from the main wing causes the airplane to rise. But the lift being behind the center of gravity also creates more pitch force which balances the pitch force from the front elevator. So as the airplane responds to the control input the effect of the front elevator is reduced.

When the front elevator pitches up its lift increases and the whole airplane pitches up. The increased lift from the main wing causes the airplane to rise. But because the lift is behind the center of gravity it also increases the down pitch force from the main wing. This force increases the more the plane pitches up and this balances the up pitch force from the front elevator. So as the airplane responds to the control input the effect of the control input is reduced. Thats negative feedback which counteracts the positive feedback from the front horizontal rudder and it greatly improves the stability of the airplane.

The results of flight test in September 1905 gave the Wrights confidence that they had solved the problem of controlled heavier than air powered flight. The control was so good that many flights ended only when the plane ran out of fuel. In two years of work the brothers found that they had to trade some efficiency to get the stability needed to make a flyable airplane. In 1908 they modified the 1905 flyer to carry two people in an upright seating position and test flew it at Kitty Hawk N.C.. Then they went off to show the world how to fly.

In 1910 the Wrights built a transitional plane to test using a rear mounted elevator. It had both front and rear elevators and demonstrated improved stability. By this point in time the engines were producing enough power that the benefits of the front elevator on power requirements no longer outweighed the negative effects on flyability. They quickly designed the Model B which had a single rear mounted elevator.

Much of the information in this paper is based on the writings of the Wright Brothers and their correspondences with other aviation pioneers as presented in "The Papers Of Wilbur and Orville Wright" edited by Marvin W. McFarland, McGraw-Hill ISBN 0-07-136376-9

The positive/negative feedback discussion is original to me but is based on standard control theory. The sail boat rudder analogy is original to me but I believe it was part of the Wright Brothers thinking at the time. The weathervane stability discussion is original to me.

I highly recommend reading Martin Simons "Model Aircraft Aerodynamics" to learn about aircraft design and control and stability issues. ISBN 1-85486-190-5

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