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Free-Flight Evaluation of Forebody Blowing for Yaw Control at High Angles of Attack

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Abstract

Forebody blowing is a concept developed to provide yaw control for aircraft flying at high angles of attack where a conventional rudder becomes ineffective. The basic concept is fairly simple. A small jet of air is forced out of the nose of the aircraft. This jet causes a repositioning of the forebody vortices in an asymmetrical fashion. The asymmetric forebody vortex flows develop a side force on the forebody which results in substaintial yawing moments at high angles of attack.

The purpose of this project was to demonstrate the use of forebody blowing as a control device through free-flight evaluation. This unique type of testing was performed at the NASA-Langley 30- by 60- Ft Tunnel. From these tests, it could then be shown that forebody blowing is an effective method of maintaining yaw control at high angles of attack.

Prior Efforts

Before joining this project, much work had already been completed towards the same end. Primarily, the model configuration had been decided upon and constructed. Furthermore, static tests were performed to determined the aerodynamic characteristics of the model.

The configuration chosen for the model was one of a 'generic' fighter aircraft. In particular, the configuration is very similar to an old NASA design which was used to evaluate configuration effects on stability characteristics. The design features a rudder, differentially moving horizontal tails, and ailerons in addition to the blowing ports along the forebody. The model was constructed by the Eidetics Corporation and then brought to NASA-Langley's 30- by 60- Ft Tunnel for static testing.

A static test is one in which the aircraft is mounted rigidly inside a wind tunnel. By placing each of the control surfaces at different positions under various conditions, the aerodynamic qualities of the model can be determined. This is particularly important for developing a control system for an aircraft. One must know what effect each surface will have on the aircraft in order to control the aircraft.

Development of Control System

In order to actually fly the model, a suitable control system had to be developed. In particular, a control system which incorporates the effects of forebody blowing. The first step to this process is determining the stability of the aircraft. At all angles of attack, the aircraft must remain stable in both roll and yaw. Generally, the basic aircraft with no control surfaces remains stable. However this is not always the case at high angles of attack. If it is not stable, proper inputs to the control surfaces may be needed to obtain stability.

Once stability is obtained, the maximum expected roll rates can be determined. One major limiting factor to roll performance is the requirement of roll coordination. For an aircraft at a high angle of attack, it is necessary to couple yaw commands with roll commands so as to avoid undesirable sideslip. However, yaw control induced by the rudder is greatly decreased at these angles of attack. It is at this point that forebody blowing becomes necessary. However, there is generally still not enough yaw performance to match the roll capabilities and roll rate limits must be set. Using the controlts available to meet the conditions of stability and roll coordination gives some idea as to the theoretical capabilities of the model and a starting point for refining the control system.

Finally, the control system was developed as a block diagram. Two separate control systems were developed. One for the lateral control system and the other for the longitudinal control system. The longitudinal control system is a fairly basic system. The only control surfaces are the horizontal tails and thrust vectoring. Thrust vectoring was being added to the original model to give added control at high angles of attack if necessary. Similarly, this system only contained three inputs. One each for the pilot's stick and trim knob and then a feedback input of pitch rate. The pitch rate feedback was used as a dampening mechanism to prevent the model from oscillating. An angle of attack feedback was originally included to limit the angle of attack but it was never employed during free-flight.

However, the lateral control system is much more complicated. This control system used the rudder, ailerons, differential tails, thrust vectoring, and forebody blowing as control surfaces. Furthermore, the pilot's stick and trim knobs were accompanied by roll rate and yaw rate dampers, sideslip feedback, and roll coordination inputs. Also, switches were required to bypass almost every feedback loop and control surface if desired. The following page illustrates this control system.

One major difficulty in developing this control system was the nature of forebody blowing. The blowing is effectively on or off which is unlike the other surfaces which can travel through a range of motion. Therefore, it is only possible to get the entire effect of blowing or no effect at all. This phenomena is produced for two reasons. First of all, the valve controlling the blowing can only be open or closed. And secondly, static data showed that the yawing moment caused by the forebody blowing was very nonlinear with respect to the air pressure.

Finally, a combiner was developed to coordinate the horizontal tail motion commanded by the longitudinal system with the differential tail motion commanded by the lateral control system. Once this was finished, the system was ready to be tested through simulation.

Simulation

In order to refine the control system, the SIMULINK toolbox for the computer program MATLAB was used. In SIMULINK it is possible to model the entire control system. Furthermore, the aircraft itself can be modeled through a series of state-space equations. These state-space equations employ the control surface deflections as inputs and output the various states of the model. In particular, the state-space equations output the roll and yaw rates, the sideslip angle and roll angle for the lateral control system. These outputs are then sent back into the control system to determine the deflection of the control surfaces.

Then, various gains can be placed into the control system for a given angle of attack and the resulting aircraft response can be determined for a given stick input. By changing the various gains in the control system, an optimal setup could be found for each angle of attack.

A similar process was repeated for the longitudinal system. Again, this was much simpler than the lateral system. Once the gain schedules were completed, the control system was turned over to the programmer who wrote the actual code to be used during free-flight.

Model Preparation

Once the control system was finished, the next stage was to finish preparing the model for free-flight. The same model that was used during the static tests was converted for free-flight. This process consisted of adding an actuator to power each control surface, installing the thrust components including thrust vectoring, and adding the data acquisition equipment. Most of this work was completed by technicians while the control system was being developed. After these components were added, the model was weighed and balanced. The additional weight of the actuators caused the aircraft's center of gravity to shift rearward. Therefore, it was necessary to add a relatively large mass to the nose. Once this was done, the true moments of inertia along all three body axis could be determined by swinging the model and measuring the natural frequencies. The actual moments of inertia were then used to update the predicted response characteristics of the model.

The next stage was to lift the model into the tunnel and prepare it for free-flight. Air hoses and electrical wires were attached to the model at the center of gravity. Finally, each control surface was calibrated and the model was ready for free-flight.

Free-Flight

Free-flight wind tunnel testing is unique to NASA Langley's 30- by 60- Ft Tunnel. The tunnel is designed with an open test section which allows enough room and the proper facilities to actually fly a model within the tunnel. Compressed air is used to provide thrust and to power the actuators which move the control surfaces. Electrical wires are also attached to the plane to relay data between the plane and the control computers. These wires are attached to the aircraft at it's center of gravity to avoid affecting the aerodynamics as much as possible.

The plane is flown by three separate pilots. One pilot is located below and behind the model. This pilot is responsible for the yaw and roll control of the plane. The other two pilots sit above and beside the model. One is the pitch pilot and the other controls the thrust. This setup allows the plane to be actually flown under controlled conditions with no risk to human life at a relatively cheap cost. Furthermore, the control system can be quickly and easily altered from the control room in case of any unexpected problems.

For this test, the free-flight program was to consist of several aspects. The primary objective was to show that the model could be flown at high angles of attack with the use of forebody blowing. To show this, the model was to be flown at a certain angle of attack with the use of thrust vectoring. Then, forebody blowing would be engaged and the thrust vectoring turned off. Finally, the blowing would be disengaged. At this point, the model would probably become unflyable. This would then show that the blowing provides enough control to fly at that angle of attack which was not possible without blowing. This was to be performed throughout a wide range of angles of attack to fully evaluate its flight envelope with and without forebody blowing.

A second object of the experiment was to determine the reaction time of the blowing. If the vortices caused by the forebody blowing took too long to form, the blowing would become impractical. To determine this, the aircraft was to be flown steadily without blowing. The blowing would then be manually engaged for a second or so and the corresponding response could be recorded.

Unfortunately, the free-flight program met with many problems. The most common problem was one where the rudder became uncontrollable. The nature of the problem was never discovered, but it caused a stop for repairs several times. Each time, the rudder resumed working properly after a short period of time for no apparent reason. Another problem was a large amount of noise in the electrical system. Again, the cause of the noise was never discovered but it was enough to cause a great deal of tail flutter and it made the data less accurate.

However, we were able to make several runs where sufficient data was obtained on the response time for the blowing. Finally, the rudder and horizontal tails were completely disconnected. This solved the noise and rudder problems. However, the plane was now flying with only thrust vectoring and ailerons. This configuration proved to be adequate since the model was still flyable. Testing was done from thirty to fifty degrees angle of attack. It was clearly shown that the plane could fly with only forebody blowing up to fifty degrees. Static data estimated the maximum angle of attack without blowing to be around 35-40 degrees. Therefore, an increase of a minimum of ten degrees was obtained with only the forebody blowing. However, expected results with the use of the conventional rudder and tails would have been around sixty degrees angle of attack, an increase of twenty-five degrees.

Data Analysis

Upon completing the free-flight testing, the next step was to analyze the flight data. There were two main objectives to be gained from the flight data. The first was a quantitized value for the response time. These were obtained by looking at the instances where the blowing was turned on and then off manually. The second objective was to ensure that the forebody blowing had the same characteristics during flight as it did for the static tests. This was done by examining the periods of flight where only forebody blowing was being used. To do this, yaw velocities were differentiated to find yaw accelerations. These accelerations were then used to find the yawing moments and non-dimensionalized to find the blowing derivatives. Finally these derivatives were compared to the static derivatives found earlier.

Conclusions

Although the free-flight program experienced many problems and an inadvertent crash halted the program early, most of the original objectives were satisfied. It was clearly shown that forebody blowing is an effective control mechanism at high angles of attack. The model was able to fly at high angles of attack while using only the forebody blowing for yaw control. Unfortunately, a complete envelope expansion with and without forebody blowing was not possible. This fact makes it more difficult to analyze how great of an increase in angle of attack that forebody blowing provides over the conventional rudder and tail setup.

The experiment allowed for an accurate representation of the response time. The time from the start of blowing to the maximum acceleration due to blowing is between .1 and .25 seconds. This is an excellent result because it shows that it is quick enough to be effective.

The free flight program met with many challenges and difficulties. But, the important result of demonstrating the effectiveness of forebody blowing was successfully accomplished. The possibilities of forebody blowing are clearly evident and should be examined in greater detail.