LONGITUDINAL ACTIVE STABILITY: KEY ISSUES FOR FUTURE LARGE TRANSPORT AIRCRAFT

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Abstract

Aircraft optimization process pay a strong attention to weight and drag, especially for large aircraft that have severe cruise performance objectives. This paper shows how to reduce the tailplane size, using a concept of "active stability", i.e. reducing the aft CG margins provided an adequate system is always present to restore a same or even higher controllability level than conventionally "passively stable" aircraft.

Modern flight control and autopilot systems do provide active stability whilst they are operating in non failure state. In order to take full benefit of active stability to reduce tailplane size, flight control system architecture must be designed in such a way that all the failure state including reversion to the backup mode provide active stability.

The backup system is based on a simple feedback using a pitch rate gyrometer parallel to the normal flight control system.

Several simulator sessions and test flight have been performed in order to validate the concept and prove that such design is viable. Information given by this flight test campaign show a very promising way, the aircraft with active stability system being very easy to fly at maximum aft CG, both in nominal non failure state and in backup mode simulation.

1 The challenges of tailplane sizing

Large aircraft are also long haul aircraft. Therefore, it is essential to design them in order to have the best cruise performance in order to offer a large payload weight to the customer associated with a large range at this payload. This must be obtained keeping an operational flexibility for aircraft loading, and ensuring a good safety behavior in all cases.

Tailplane size participates to these objectives. Minimizing the size of tailplane reduces the aircraft empty weight, but also reduces the drag by simple decrease of the wetted surface. On the other hand, a smaller tailplane gives usually a smaller operational Center of Gravity (CG) range for given safety objectives, and the tailplane size is a compromise.

With the extensive use of electrical flight control laws, classical design of tailplanes can be challenged, and size can be reduced while maintaining safety level, and with a constant operational CG range for the customer.

2 Tailplane sizing of a new project aircraft

In order to clearly understand the effect of active stability on tailplane size, we must first recall the way to size a tailplane.

2.1 Tailplane size effect on design criteria

Tailplane sizing is based on a set of design criteria that are generally linked to safety in corner points of the flight envelope. Some of them are related to forward CG limit, the other ones to aft CG limit. We can illustrate on one of them the effect of the tailplane size for all of them: a size increase allows more forward "forward CG limit", and more aft "aft CG limit".

For example at forward CG limit, a 40° bank turn is required up to the lowest operational speed (VLS). This requires a large lift coefficient CL . In order to balance the aircraft at the most forward CG and at high weight, tailplane will be on its nose up stop, and elevators also on their stop. Lift momentum is balanced by downlift created by the set tailplane + elevators. The more downlift the tailplane can create, the more lift momentum it will balance, what corresponds to more forward CG at a given weight when size increases.

2.2 Scissors diagram principle

All forward and aft CG criteria are synthesized in a diagram called "scissors diagram".

An initial configuration of aircraft gives objectives of CG limit (aft CG & forward CG) given by operational loading constraints. These objectives of CG are translated into a CG range (Aft CG-forward CG) and the optimal tail plane size is obtained when this CG range is simultaneously in contact with forward and aft criteria.

If the obtained CG limits are not the initial configuration ones, a wing shift is necessary in order to harmonize loading requirements and handling qualities capacity.

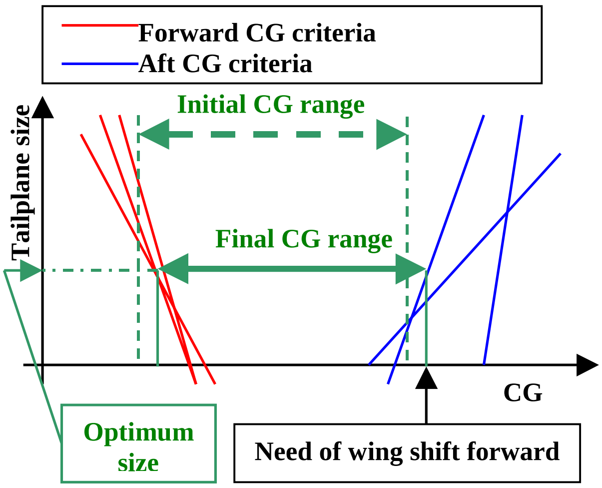


Fig. 1

2.3 Effect of active stability on tailplane size

Aircraft are generally sized at aft CG by a stability criterion: margin relative to the manoeuvre point. It will be described later. A natural aircraft –that is to say a mechanically controlled aircraft or an electrically controlled aircraft with a direct link from pilot control to pitch control surfaces- cannot be flown too close to the manoeuvre point and a given margin has to be taken for design.

The purpose of "active stability" is to challenge this margin, provided the pilot will never have to fly a natural aircraft by adapted system means.

The effect on the scissors diagram is to shift backwards the aft limit, and thus open the scissors and allow to have the same CG range with a decreased tailplane size. The wing position has to be adapted.

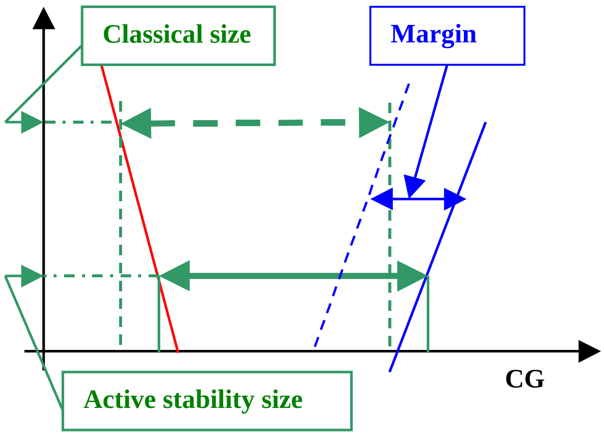


Fig. 2

The tailplane size decrease can be in the order of 10%, keeping the aircraft still on the dynamically stable side, that is to say close to the manoeuvre point but not aft from it.

2.4 Effect on flight CG

As it can be seen in fig2, the CG range with active stability is globally shifted backwards. Modern long haul aircraft have a CG regulation in order to improve fuel consumption flying at aft CG. Trim downlift is minimized and drag improved. As active stability allows more backward CG, it tends to improve trim drag, what is an other good point added to weight decrease and friction drag improvements.

3 What is the manoeuvre point?

In order to understand the challenge of active stability, it is essential to know the behavior of the aircraft close to the sizing criterion at aft CG

3.1 Simplified physical explanation

We start with an aircraft trimmed at a given CG. When the pilot performs a pull up and balances this pull up with elevators, he has to balance an increase of lift located a the neutral point plus the natural pitch damping of the aircraft (fig 3).

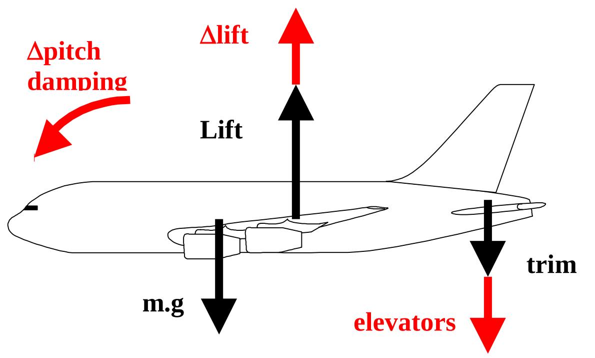


Fig 3

When the CG is more aft, the momentum created by the same Δlift decreases as the lever arm decreases also (pitch damping is almost constant). As a consequence, elevator will have to be less deflected (fig 4).

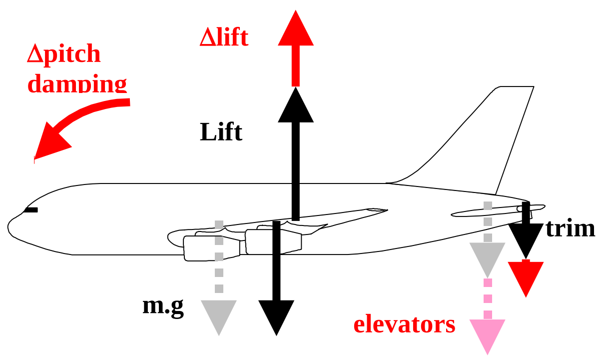


Fig 4

We are thus able to plot a curve showing for a given Δlift the required elevators vs CG. The definition of the manoeuvre point is when the curve crosses 0° axis, which means that the pull up is balanced at the trim position without need of elevator.

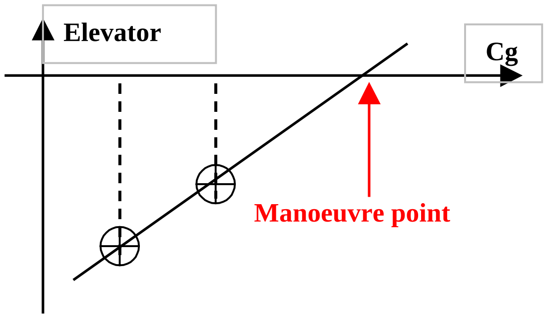


Fig 5

This explanation is only simplified as some complementary terms are neglected, but allows to have a clear understanding.

3.2 Why is it a problem for pilots?

When a pilot has to initiate a pull up, he has to increase the angle of attack with a nose up input, that will always be with nose up elevator whatever the CG position. Afterwards, the pilot has to stabilize and balance this pull up, and if we look at figure 5, we can see that the position of elevators depends on the CG position with respect to the manoeuvre point. When the CG is in front of the manoeuvre point, then the elevators will be deflected nose up, so in a conventional direction with a pulled back stick. On the other hand, with a CG aft from the manoeuvre point, the elevators need to be in a nose down position that is totally unusual for a pilot. With a natural aircraft, the stick will be pushed forward.

For a pilot flying a conventional aircraft, i.e. with CG in front of the manoeuvre point, the stick deflection is in the same direction when he initiates the manoeuvre and after controls it. The aircraft is dynamically stable that is to say that if the pilot releases the commands, the aircraft will naturally stop the manoeuvre.

If the CG is aft from the manoeuvre point, the stick deflection is of opposite sign. The aircraft becomes unstable as the manoeuvre amplitude will increase if the pilot releases the commands.

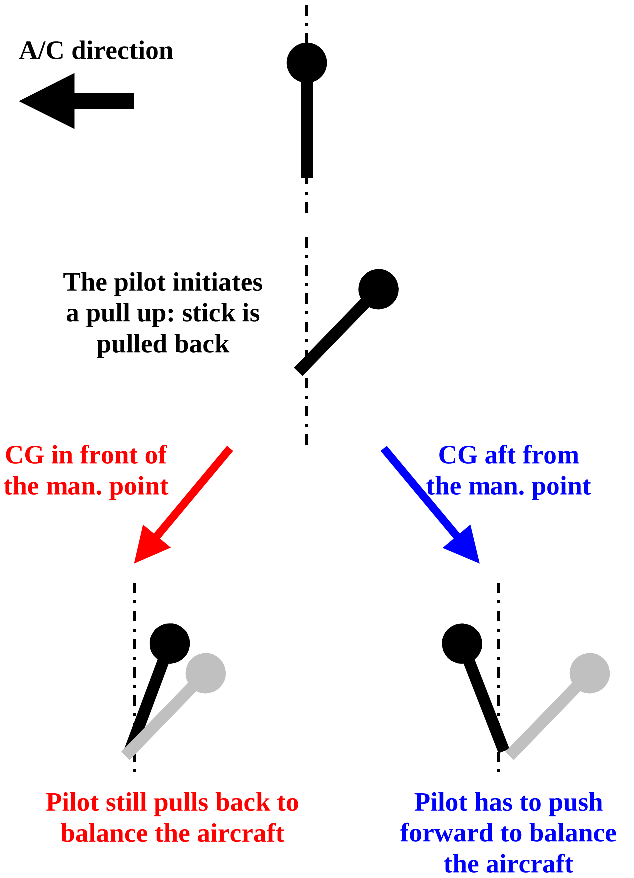


Fig 6

3.3 Simplified equations of the manoeuvre point

It is possible to have an analytic approach of the manoeuvre point that allows to isolate the important coefficients and better know how to solve the problem of a flight close to the manoeuvre point.

This approach will be performed with a rigid aircraft. Flexibility coefficients will add complexity but will not allow a better understanding.

During a pull up, we can write the increments of pitching moment corresponding to elevators, load factor and pitch rate, and write that they balance each other:

$$\Delta Cm(\delta q)=[Cm_{\delta q}+CL_{\delta q}\,(Xf-Xg)].\ \delta q \qquad (1)$$

$$\Delta Cm(Nz)= CL\ [Xg-Xf].\ \Delta Nz \qquad (2)$$

$$\Delta Cm(q)=[Cm_q+CL_q\,(Xf-Xg)].\ q.l_0/V \qquad (3)$$

During a pull up, pitch rate and load factor are linked by

$$q=\Delta Nz.g/V \qquad (4)$$

The manoeuvre point definition is

$$\delta q/\Delta Nz=0 \qquad (5)$$

And it gives the simplified formulation:

$$Xg = Xf + \frac{Cmq.\frac{gl_0}{V^2}}{-CL+CLq.\frac{gl_0}{V^2}} \qquad (6)$$

All these coefficients have an evolution with mach, and the critical position of manoeuvre point is at a mach that depends on aircraft aerodynamics.

This simplified equation allows the following conclusions:

- Manoeuvre point is directly linked to neutral point.
- Damping produced by pitch rate (Cmq) is the main contributing factor to push the manoeuvre point beyond the neutral point.
- The manoeuvre point is all the more forward as CL is high, that is to say if aircraft is heavy in given flight conditions.

4 Impact on the aircraft design

4.1 Flight conditions to be covered

An aircraft manufacturer has to demonstrate that the aircraft is in accordance with the regulations, but also covers in-house cases eventually outside of the certification process. For an aircraft with an electrical flight control system that relies on a set of computers and on electricity, it has been chosen to cover the possible loss of all electricity on board or the total loss of all the flight control computers. These are forfaitary failures, which occurrence is demonstrated to be Extremely Improbable (probability<10^{-9}). This choice to cover these cases with a backup system is a permanent characteristic of Airbus Fly by Wire design since the introduction of A320.

On many aircraft, this backup is performed by keeping an additional mechanical system working in parallel with the electrical flight controls. In backup conditions, the pilot has a natural aircraft in, and the CG aft limit has to be designed taking this fact into account, so taking a margin with respect to the manoeuvre point. Tailplane is sized in this way.

Therefore, if the aircraft tailplane is sized while taking benefit of active stability it is no longer possible to have a mechanical device as backup system.

4.2 Backup principle

Manoeuvre point is a physical fact, and the elevator will always have to be deflected in a non conventional direction when the CG is behind the manoeuvre point. The consequence is that the backup system needs a permanent stabilizing term as part of the control device.
As it can also be seen through the manoeuvre point simplified equation 6, the pitch rate damping (Cmq). has a beneficial effect on it. The principle of the backup system will be to improve artificially Cmq, instead of improving it physically when increasing the tailplane size. Its becomes then obvious that the backup system will work measuring the pitch rate q and producing a pitch momentum with the elevators (pitch damper).
We must keep in mind that we must produce this feedback despite the total loss of electricity on board. Therefore, the electric energy required to make this system work has to be produced independently from the main electrical system. It can be produced using hydraulic energy that is of course still available with a micro local electrical generation.

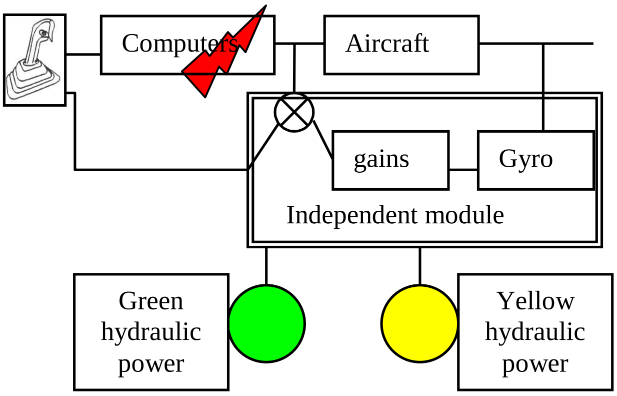


Fig 7

4.3 Backup design constraints

In order to perform its function with a maximum reliability and the minimum maintenance burden, backup has to be as simple as possible, and should use the rawest possible information, (ideally without any external additional information) to make the aircraft flyable.

Backup system has to work in the whole operational flight envelope, from the greatest speeds or mach (VMO/MMO) up to the lowest speeds in high lift configurations, in order to cover an eventual farfaitary failure in cruise but also during take off or landing phases.

It must also work in the whole weight/CG operational envelope, from max take off weight (MTOW) down to the minimum weights, and from forward to aft CG limits.

If we want that no external information be given to the backup module, it means that the gains have to be a compromise between all these cases. The wider the flight domain is, the more difficulties we will have to find adequate gains.

Practically, it appears that the compromise has to be found between high weights at aft CG and low weight at forward CG.

At high weights and aft CG, the aircraft CG is behind the neutral point, and the criticality is the divergence rate. At low weights and forward CG, the aircraft can have poor angle of attack oscillation damping, that is prompt to aircraft-pilot coupling (APC)

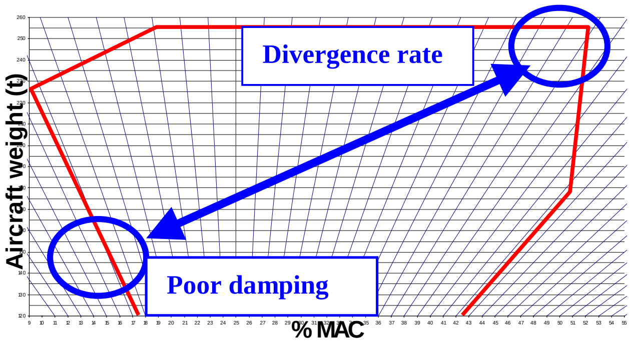


Fig 8

5 Concept validation

Since years of Aerospatiale Matra Airbus progressive built-up of expertise in flight control systems, we have resorted to flight test in order to validate any significant new concept (i.e. 1978 Concorde campaign for sidestick and C* law, 1983/85 A300 MSN3 for A320 control laws and protections).

In a consistent way , a large set of tests have been performed in order to demonstrate that it is viable to fly with active stability. A340 test aircraft has been used for that purpose. Flight Control computers have been modified in order to take into account more aft CG in the design of the normal control laws (high level laws that are used every day to control the aircraft with a large set of information), and a simulation of a backup control module has been also implemented, using the information of an external gyrometer.

5.1 Flight tests

A special loading of the aircraft allowed to have the real CG moved back to the manoeuvre point. The purpose of the flight test campaign was to demonstrate:

- That it is possible to design normal laws that give good pilot and passenger comfort, and good piloting precision.
- That it is possible to design a backup law with common gains at forward and aft CG, heavy and low weights.

Flights have been performed. Some at aft CG, at medium weight and at the manoeuvre point, the other one a high weight and as aft as the loading possibility of the aircraft allowed, so 3% in front of the manoeuvre point. Other flights at forward CG, low weight allowed to check that gain found adequate at aft CG were always adequate at forward CG.

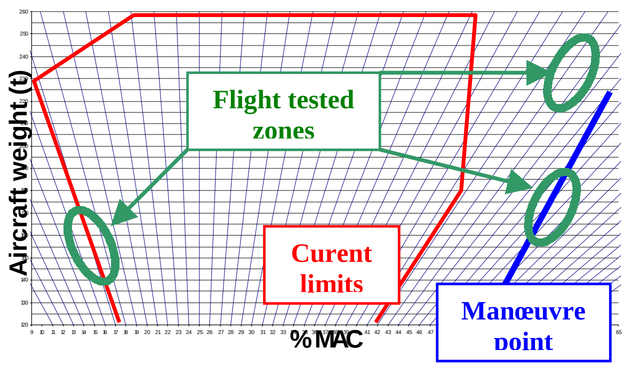


Fig 9

The conclusions of flight test pilots are the following:

As normal laws are concerned, and as long as gains are adapted to the current CG, there is no difference between a flight at the manoeuvre point and a flight with the current aircraft at its certified limits. This statement is based on piloting comfort and precision. As far as it was possible to observe, passenger comfort seemed unaffected by the flight at more aft CG.

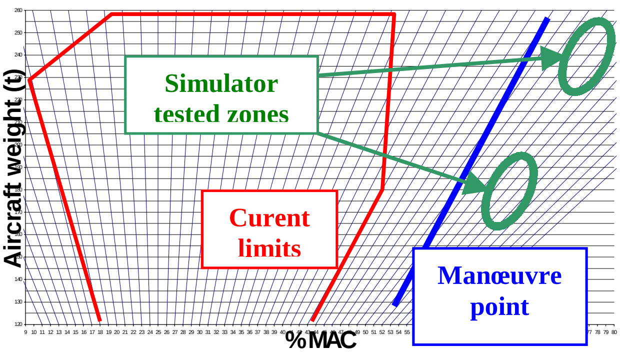
About backup law behavior at the manoeuvre point, they found it very efficient and precise, indeed more easy to fly than the direct law of the basic aircraft at the certified CG. Therefore, their conclusion was that backup law was not only flyable at the manoeuvre point but was also providing better crew workload when compared to an aircraft flown in direct type of control law(i.e. without pitch damper) and the maximum associated possible aft CG.

5.2 Simulator tests

The same normal and backup laws have also been tested on simulator. The purpose of such tests was to explore flight conditions that were not reachable with the test aircraft, and perform some upset manoeuvre that it was not reasonable to do in flight.

Simulator test have been performed at all weights up to 5% behind the manœuvre point in order to test the robustness of laws. The same tests as in flight were repeated. In order to complete the test, transitory between normal flight control laws to backup laws with the aircraft in severe conditions (pull up, turn at high bank angle) have also been tested.

The same behavior as in flight has been observed and it has been found easy for a pilot left in severe conditions in backup law to recover a safe flight attitude.



6 Impact on aircraft systems

6.1 Backup control module

As we have seen before, the aircraft has to be fitted with an equipment that will be totally independent of the nominal flight control loop, and especially that will work without electrical supply. In order to be robust, the design aim is to cover the whole flight domain in speed, weight, CG,… with a single set of gains.

6.2 Servocontrols

At aft CG where active control is required, and even if the normal flight control can easily and properly stabilize the aircraft, the elevator activity in turbulence will be increased. Additionally, a backlash or other mechanical non linearity may have stronger influence on comfort than at less aft CG.

The first point deals with servocontrol design for fatigue, and has to be taken into account by the servocontrol design in order to ensure the same life duration as other aircraft servocontrols.

The second one deals with specification of servocontrols built and monitoring tolerances. During flight test campaign, several non linearity of servocontrol have been simulated by additive inputs on the electrical servocontrol monitoring order. The effect on passenger comfort and on pilot comfort and precision has been observed, and it has been found that with the current capacity of servocontrols, an adequate level was reached. This indicates that active stability will not have any significant impact on servocontrols tolerance design or rigging.

6.3 Sidestick

Aircraft stabilization at aft CG requires high speed surfaces. Therefore, elevators have to be used instead of Trimmable Horizontal Stabilizer as on previous aircraft. The backup module will thus directly command the elevator servocontrols. It becomes then natural that the pilot link between cockpit and backup module has to be the sidestick instead of the trim wheel. With a completely electrical backup system, it does not present any technical hurdle.

The important consequence is that the pilot will have the control of the aircraft with the sidestick he has usually in hand, and control the aircraft through high speed surfaces. The positive consequence is thus that pilots have a far better control of the aircraft in very severe failure cases than before.

7 Conclusion

Aerospatiale Matra Airbus is actively contributing to the overall design optimization of future Airbus products. One area of such optimization is the quest for minimum tailplane size and associated reduced weight and drag. While still satisfying loadability constraints, this can be achieved by resorting to flying at aft CG. This obviously reduces natural longitudinal dynamic stability of the aircraft and must be compensated by permanently available active stability.

Aerospatiale Matra Airbus has designed a system architecture which provides this active stability in normal non failure case and in failure cases including arbitrary loss of electrical supply and/or loss of all main digital computers.

The control laws associated with the contemplated system architecture, both in normal and backup modes, have been successfully flight tested on A340 prototype in a wide range of conditions including flying at the manoeuvre point.

The results have been judged satisfactory by the flight crews and the principle is considered validated.

This clears the way to the introduction of longitudinal active stability and optimized tailplane size for future airbus projects.

Glossary

δq	*elevator deflection*
$Cm_{\delta q}$	*pitching moment gradient due to elevator*
$CL_{\delta q}$	*Lift gradient due to elevator*
Xf	*Neutral point vs mean aerodynamic chord*
Xg	*CG vs mean aerodynamic chord*
CL	*Lift coefficient*
ΔNz	*Load factor increment*
q	*pitch rate*
Cm_q	*pitching moment gradient due to pitch rate*
CL_q	*Lift gradient due to pitch rate*
l_0	*aerodynamic mean chord*
V	*True air speed*