ACOUSTIC CONTROL OF LAMINAR SEPARATION BUBBLES

Correa, L.G.N. , Entz, R.M.U. , Cosin, R. , Catalano, F.M.
Aerodynamics Laboratory - Engineering School of São Carlos - University of São Paulo

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Abstract

An acoustic source is used to control the size and location of the laminar separation bubble on a FX63-137 airfoil. This is a way to reduce the negative bubble effects on the performance of aircraft flying at low Reynolds number.

The most amplified excitation frequencies are computed with the linear stability theory, considering the velocity profiles obtained using a panel code with coupled boundary layer. Wind tunnel testing is then carried out and the bubble characteristics are determined with surface flow visualization. Using the acoustic excitation, a reduction of up to 25% in the bubble size could be achieved.

1 Introduction

Laminar separation bubbles have an impressive influence on the performance of almost all aircraft flying at low Reynolds number. Bubbles can be found in unmanned aerial vehicles (UAVs), micro-air-vehicles (MAVs), high-altitude airplanes, sailplanes, ultralights, human-powered aircraft (HPA), propellers, slats, wind turbines and other applications with chord Reynolds number ranging from approximately 10,000 to 500,000.

Bubbles also induce changes in the lift and pitching moment, leading to aircraft stability problems. Numerical simulations revealed that bubbles are a noise source, related to the vortex shedding and to the transition/reattachment region [1]. An active control is then a possibility to reduce the noise generated by slats, as bubbles are present in the boundary layer associated with this device, which is used in almost all commercial airplanes.

For all these reasons, bubbles are not desired in most applications and there are several means to avoid them. The most common is the use of turbulators, which consist in small geometric discontinuities on the wing surface, providing enough energy to lead to transition. Recently, active methods are also being well studied, specially those regarding to surface heating, oscillatory mechanicals devices and boundary layer blowing/suction, including synthetic jets [2].

The main advantage of these methods is the possibility of using them in several flight conditions, while turbulators work only in certain situations. Experimental results show that turbulators may double the total drag in unfavorable conditions [3], making the use of an active control the most satisfactory way reduce the negative bubble effects for a wide range of flight situations.

Investigations have shown that an acoustic source can be used as an active control [4] for laminar separation bubbles. This method is then investigated in the present work, in which the most amplified frequencies are computed with the stability theory [5].

2 Theoretical Background

Separation bubbles are created by an adverse pressure gradient in a laminar flow. In the first stage of the process, forced disturbances generated by the model (vibrations, roughness) or in the freestream (noise and turbulence level) create an effect inside the boundary layer, originating initial conditions for the transition through the receptivity process. These small disturbances

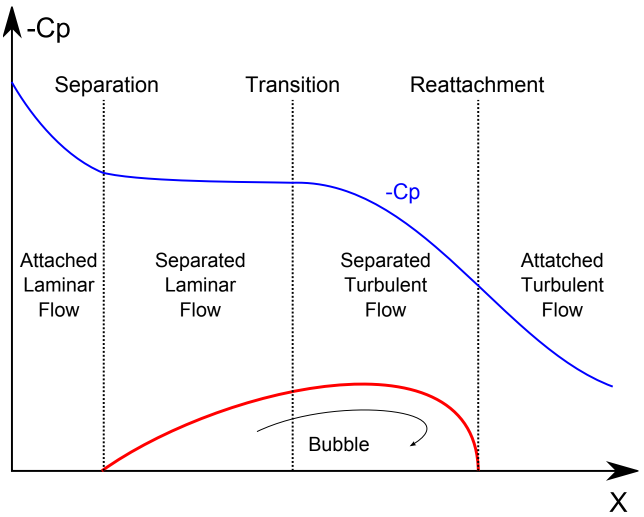


Fig. 1 Typical flow structure in a laminar separation bubble

are then amplified exponentially according to linear equations and, considering a low disturbance environment, the instability mechanism in the attached boundary layer is primordially of Tollmien-Schlichting (TS) type.

However, primary shear layer instabilities (Kelvin-Helmholtz or KH instabilities) become dominant downstream to the laminar separation. The velocity profile at this region quickly amplifies the disturbances in the boundary layer, triggering non-linear effects and the amplification of several modes, breaking the ordered laminar structures and causing the transition to turbulent flow.

In the process in which KH instabilities are present, a mechanism called "spanwise rollers" appears. These structures move fluid with high momentum from the external flow toward the wall, energizing the separated boundary layer, reattaching the flow and creating a closed bubble. However, the pressure gradient may be too strong, in a way that the high momentum fluid entering the separated boundary layer is not enough for the reattachment, leading to the bubble burst.

To change the size of the laminar separation bubble, it is possible to excite frequencies that are most amplified by the viscous TS or the KH mechanisms, moving the transition location closer to the laminar separation. To compute these frequencies, a linear stability analysis is performed based on the velocity profiles.

2.1 Computation of flow parameters

XFOIL [6] is used to compute the pressure distributions and the boundary layer velocity profiles. It is an airfoil analysis software that uses a second order panel method with a sophisticated boundary layer implementation. A two-equation integral formulation with lagged-dissipation closure is employed to consider the boundary layers and the trailing wakes. Coupling of the inviscid and viscous regions is done via the displacement thickness, allowing XFOIL to deal with strong viscous-inviscid interactions. For transition prediction, XFOIL uses an envelope method in which the highest amplification is determined at the stations.

2.2 Linear Stability Theory

The linear stability theory accounts only for the linear growth of the instabilities, which represents the main part of the transition process and thus this theory may provide a good estimative of the transition position. However, for cases in which the initial amplitudes of the disturbances is high, the linear stages of the process are ignored and the nonlinear effects occur a short distance from the attachment line. This is called bypass transition and it is common in wind tunnel tests with freestream turbulence above 0.4% or in models with large roughness elements.

Considering only the a two-dimensional case, it is possible to obtain the well-known Orr-Sommerfeld relation using the linearized Navier-Stokes equations [7]. This method may be extended to a three-dimensional, compressible or incompressible flow [8].

To obtain the linear equations, the flow is divided in a steady flow and a perturbation flow that varies on time and space. By eliminating the base flow, as it solves the Navier-Stokes equations, a nonlinear set of equations is obtained. Then these equations are linearized, assuming that the initial disturbance is small. The disturbances r' are expressed as

$$r' = r(y) \cdot e^{i(\alpha x - \omega t)} \tag{1}$$

where x is a coordinate in the streamwise direction, y is a coordinate normal to the surface, α and ω are complex numbers. r is any flow quantity (velocity, pressure, density or temperature) and it depends only on y (parallel flow). By introducing the perturbations into the Navier-Stokes equations, a system of ordinary differential equations is obtained. This leads to an eigenvalue problem, as non trivial solutions exist only for some specific combinations of α, ω and the Reynolds number Re.

In the spatial theory, ω is a real number and α is complex: $\alpha = \alpha_r + i\alpha_i$. The local behavior of the disturbances depends on the imaginary part of α: amplified for $\alpha_i < 0$, neutral for $\alpha_i = 0$ and damped for $\alpha_i > 0$.

For practical applications on transition prediction, the e^N method is used [9]. It consists in integrating the local amplification along the curvilinear coordinate s and computing the N-factor, which is defined as

$$N = log\left(\frac{A}{A_0}\right) = \int_{x_0}^{x_1} -\alpha_i \, dx \tag{2}$$

where A is the perturbation amplitude at x and A_0 is the initial perturbation amplitude. The transition occurs at the point where the N-factor reaches a critical value obtained empirically, which depends on several environmental variables, including the freestream noise.

For this reason, transition occurs at lower N-factors for cases in which the perturbations have higher initial amplitudes. This was considered by setting the critical N-factor according to the wind tunnel turbulence level, using the relation given by Mack [5]

$$N = -8.43 - 2.4 \ln(Tu) \tag{3}$$

where Tu is the freestream turbulence level.

In the experiment, the turbulence level is around 0.17%, corresponding to a critical N-factor of 6.8. However, for turbulence levels of approximately 0.4%, another type of transition is predominant. In this case, disturbances in the freestream cause laminar fluctuations in the boundary layer or they are strong enough to enter in the boundary layer. This fluctuations initiate turbulent spots and then a fully turbulent flow is achieved. This type of transition, in which the linear growth of instabilities is not necessary, is known as bypass. Due to the relatively low freestream turbulence level in the wind tunnel used, bypass transition was not observed even with the acoustic excitation.

3 Experimental Apparatus

Experiments were carried out in an open circuit wind tunnel. The test section has $250mm \times 450mm$, the turbulence level is 0.17% at $15m/s$ and the maximum chord Reynolds number is $600 \cdot 10^3$. A Wortmann FX63-137 airfoil with $240mm$ chord was used.

Sound signals of several frequencies were generated with Matlab and sent to a $200W$ amplifier and two speakers at the wind tunnel intake.

Bubble size and position were measured with surface flow visualization. Although this technique is not very accurate, it gives a reasonable indication on the bubble behavior with the sound excitation. More accurate results may be obtained with naphthalene or using a thermographic camera [4].

4 Numerical Results

The Reynolds number chosen for the numerical and experimental results is $260 \cdot 10^3$ and the angle of attack is 4 degrees. This configuration has a large laminar separation bubble after the maximum airfoil thickness and it is ideal for the current investigations. The pressure distribution computed with XFOIL for this configuration is in Fig. 9 and it shows a large separation bubble on the upper surface. Using the critical 6.8 as the critical N-factor, the laminar separation occurs at $x/c = 0.53$, the reattachment at $x/c = 0.67$ and the total bubble size is $0.14c$.

Boundary layer velocity profiles were computed at four stations, according to the Table 1. The non-dimensional profiles are in Fig. 3. When

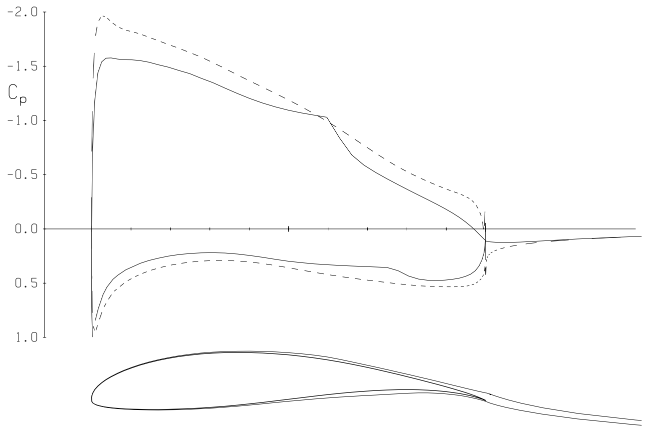


Fig. 2 Pressure distribution for $\alpha = 4°$

a bubble is present, there is an inflection point in the velocity profile, increasing substantially the growth rate of small disturbances. These velocity profiles inside the bubble are similar to those present in free shear layers and this instability is considered KH dominant.

Station	x/c	Condition
1	0.45	Before the laminar separation
2	0.55	After the laminar separation and before the transition predicted by XFOIL
3	0.65	Separated and turbulent boundary layer
4	0.85	After the turbulent reattachment

Table 1 Stations used for the stability analysis

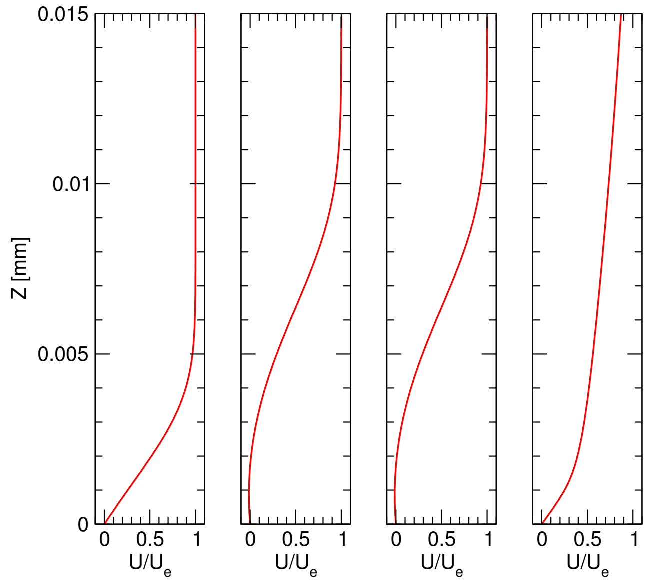


Fig. 3 Boundary layer velocity profiles used for the linear stability computations

4.1 Linear Stability Results

The TS N-factors for several non-dimensional frequencies are in Fig. 4. For the current experiment, the maximum amplification for TS disturbances at the bubble region is around 1000 Hz.

Linear stability results for KH amplification at station 2, just after the laminar separation, shows that the spatial amplification factor is maximum at $165Hz$, according to the results in Fig. 5. Frequencies from 100 to 1000 Hz were then selected for the wind tunnel testing.

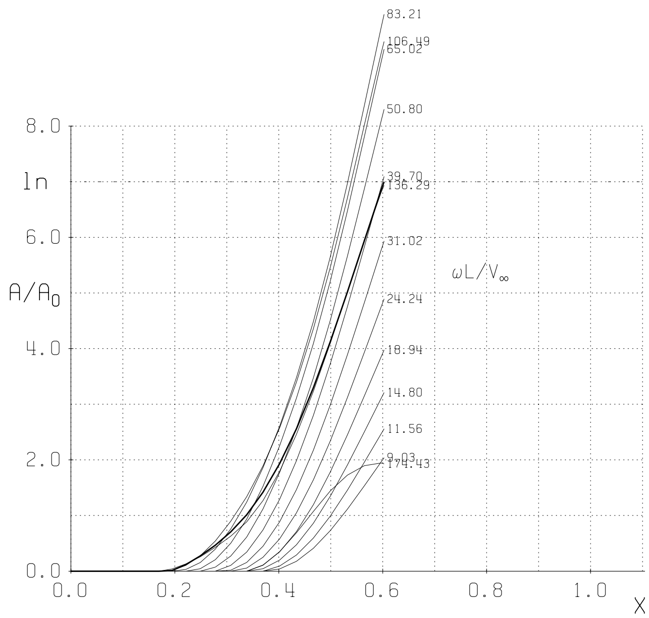


Fig. 4 N-factors for TS disturbances

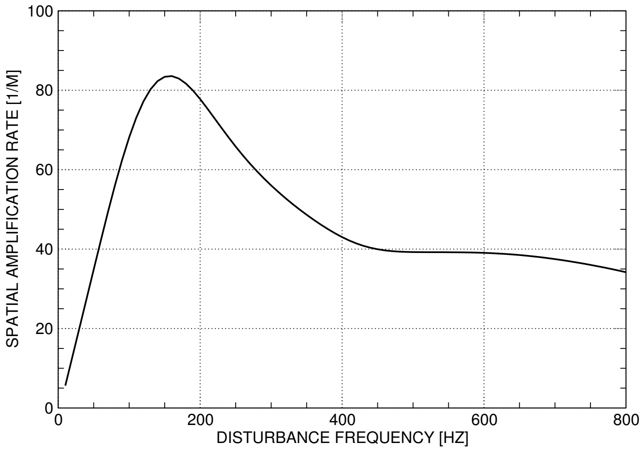


Fig. 5 KH spatial amplification for $x/c = 0.60$

5 Experimental Results

The first wind tunnel test were carried out without sound. A laminar separation bubble was observed from $x/c = 0.55$ to $x/c = 0.81$, with a total size of $0.26c$, larger than in the XFOIL results. This is quite expected due to the large scatter associated with low Reynold flow and difficulties to define a critical N-factor.

The use of an acoustic source changed successfully the laminar separation bubble. For frequencies around $200Hz$, there is a reduction of 20% in the bubble size, due to the excitation of KH instabilities. Experiment with higher frequencies were able to excite TS instabilities, achieving the maximum reduction on the bubble size. For $1000Hz$, the bubble was reduced in 25%, the largest reduction for all frequencies tested. This is close to the frequency computed by the linear stability theory that gives the maximum amplification for TS disturbances ($880Hz$). Higher frequencies were not tested in the experiment due to the large amount of harmonic distortion, as the selected speaker was designed for low frequencies.

For the intermediate range, between $300Hz$ and $500Hz$, the bubble size was only slightly changed compared to results without the sound excitations. For $400Hz$, the bubble was reduced in only 3%, strengthening the idea of two distinct amplified ranges, with frequencies between $100Hz$ and $250Hz$ for KH and above $500Hz$ for TS.

During all experiments, it was not possible to achieve a bubble breakdown, even with all the acoustic power available.

Fig. 6 Wind tunnel testing without sound

Fig. 7 Wind tunnel testing with $200Hz$ excitation

6 Conclusion

Acoustic excitations were able to reduce the bubble size by amplifying KH and TS instabilities, but it was not possible to achieve a bubble breakdown. However, an acoustic source with localized effects may be a potential candidate to reduce the bubble size in practical applications.

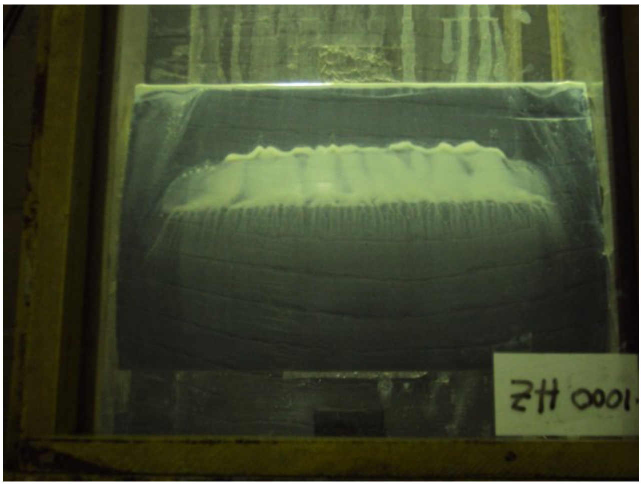
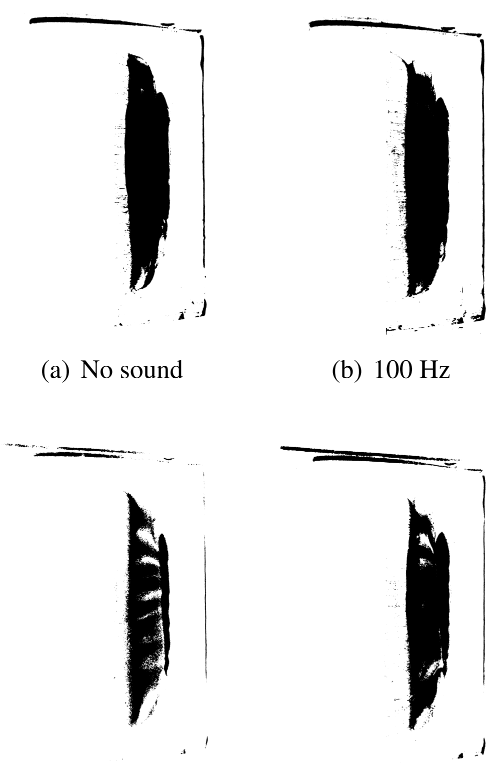


Fig. 8 Wind tunnel testing with 1000*Hz* excitation



(a) No sound (b) 100 Hz

(c) 200 Hz (d) 300 Hz

Fig. 9 Processed images of the wind tunnel results in the KH amplification range

Freq.	Bubble Characteristics (x/c)		
	Separation	Reattachment	Size
No Sound	0.55	0.81	0.26
100 Hz	0.56	0.81	0.25
200 Hz	0.57	0.78	0.21
300 Hz	0.56	0.80	0.24
400 Hz	0.56	0.81	0.25
500 Hz	0.56	0.81	0.25
1000 Hz	0.56	0.76	0.20

Table 2 Bubble size

The excitation frequencies were computed with linear stability theory and they have a relatively narrow range with high spatial amplification. This was confirmed with wind tunnel testing.

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