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INTERNAL ACCOUSTIC EXCITATION TO ENHANCE THE AIRFOIL PERFORMANCE AT HIGH REYNOLDS NUMBER

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Abstract

The ability to force air flow to follow the contour of a given lifting surface, even under the adverse pressure flow gradient, plays a significant role in optimizing the performance of lifting surface. As the angle of attack (α) increases large portion of the lifting surface will not see the flow due to the separation occurring closer to the leading edge. This creates an unsteady wake which results in loss of lift and increase in drag. In order to minimize the boundary layer separation, additional energy must be given to a low momentum fluid in the very near-wall region.

It has been found that acoustic-vibration energy, which introduces periodic energy input, delays flow separation. The approach presented herein employs acoustic and vibration excitation. Two designs were constructed and experimented upon using the 0.76 m open jet open circuit subsonic wind tunnel at the University of New South Wales, with results showing potential to reduce flow separation.

In the present study, speakers were used as means of internal excitation to vibrate the NACA 0015 wing. Various frequencies were applied on the top surface of the wing by the internally attached speakers.

When the flow was excited at a favourable frequency, the flow separation was suppressed, and delay in stall angle of attack (α_{stall}) was found to occur. Further, the relationship between the excitation frequencies (f_e), shedding frequencies (f_s) and the Strouhal numbers (Sr) was found.

1. INTRODUCTION

The study focused on internal acoustic excitation to excite the flow over a lifting body. The properties of a lifting surface were changed by various frequencies applied from the internally attached speakers. The objective was to suppress a turbulent flow to reduce flow separation. The parameters of interest were changes in lift and drag, with respect to f_e at high Reynolds number (R_e).

The NACA 0015 was the chosen cross section profile and two separate experiments were carried out incorporating the internal excitation concept. The first experiment involved using the smoke laminar wind tunnel to observe the effect of acoustic excitation over the lifting body at a low R_e. The second experiment involved observing the excitation effects at a higher R_e using the open jet open circuit wind tunnel. Both experiments showed improvement in flow characteristics over the wing when excited by the speakers.

2. SMOKE LAMINAR WIND TUNNEL EXPERIMENT

2.1 Introduction

The smoke laminar wind tunnel demonstrated flow visualization over the excited and non-excited wing at a very low air speed. Smoke filaments were generated by vaporizing kerosene in an electric boiler, which then gets injected into the wind tunnel by means of a small fan and a smoke filament rake. These smoke filaments then passed over the model or test section from which the flow pattern can be observed.

2.2 Model Fabrication and Experiment Setup

A 2 W 40 mm diameter cone speaker was chosen to excite the model wing. Further, a single channel amplifier 3.5 W along with a signal generator and a voltage generator were selected to operate the speaker. The model was constructed using balsawood and plywood. The leading and trailing edge were hand-carved to match the NACA0015 profile. The model had 65 mm span and 150 mm chord *(c)* length. A 40 mm diameter cylindrical steel tube was inserted into the model, with 1 mm slit located at 45% chord length (c) from the leading edge spar. The speaker was attached to one end of the steel tube with the other end blocked by a steel plate. The schematic diagram of the experiment setup is shown in Figure 1. The angle of attack (α) of the model was set at 30 degrees where clear flow separation over the wing surface was visible at non-excited condition. Excitation frequency was then increased slowly at a set free stream velocity (u_∞) of 2 m/s. Changes in flow behaviours were observed through smoke flow visualization.

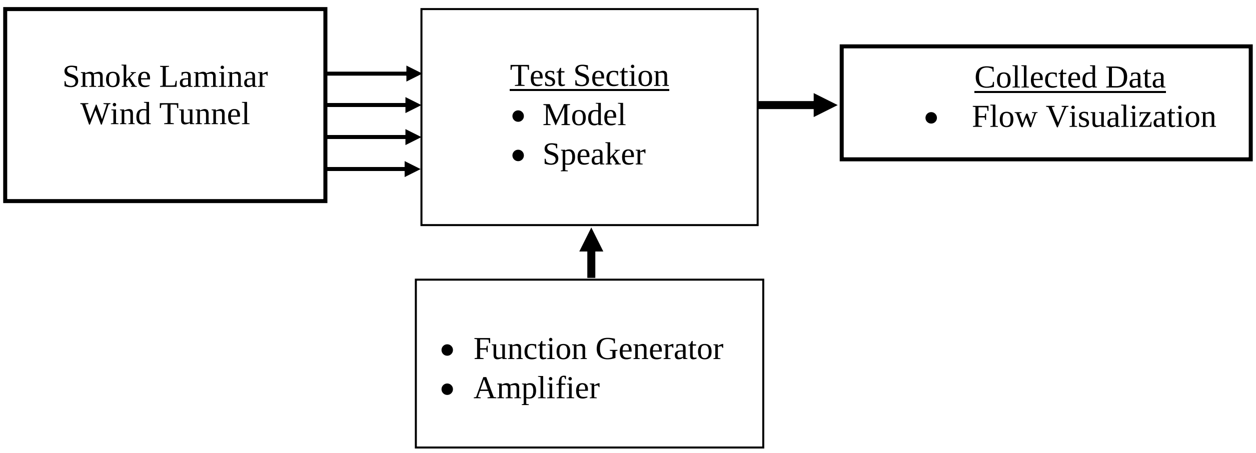

Figure 1 - Schematic diagram of the Smoke Laminar wind tunnel setup

2.3 Results from the smoke laminar wind tunnel experiment

When the speaker was on, the size of the separated flow was greatly reduced. At f_e set at 55 Hz, reduction in turbulent region and flow reattachment was observed. Further, increase in flow speed over the wing was noticed at the leading edge spar to the slit.

2.4 Conclusion and discussion

The smoke laminar wind tunnel experiment was important in the concept of this study for it showed a number of important points. Firstly it showed acoustic energy did affect the flow over the wing and delay in flow separation was found. Secondly, the acoustic excitation influenced the flow characteristics over a wing upstream of the location of excitation. Thirdly, the experiment proved the slit design concept as a plausible innovation. The improvement in flow characteristic did warrant a further investigation at a high R_e. The smoke wind tunnel was operating at a low speed laminar flow. The test speed was 2 m/s. It was expected that results for higher speed test would give similar or better results for more energy was available in the flow.

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3. OPEN JET OPEN CIRCUIT SUBSONIC WIND TUNNEL EXPERIMENT

3.1 Introduction

The model presented herein employed the same excitation method as before in an attempt to extend the finding to a lifting body at a higher R_e.

The experiment was carried out using the open-jet, open circuit, subsonic wind tunnel. The diameter of the open section wind tunnel was 760 mm with a turbulence intensity of 0.2%. The span and chord length of the test article were 590 mm and 255 mm respectively based on the blockage area ratio of the wind tunnel. The experiment was performed at a fixed u_∞ of 8.5 m/s or Reynolds number (R_e) = 1.5x10^5 (calculated below). The set conditions were: u_∞ = 8.5m/s, ρ_∞ = 1.225 kg/m^3, μ = 0.00001789 kg/ms and c = 0.255 m.

$$\mathrm{R_e} = \frac{\rho_\infty U_\infty C}{\mu} = 1.5 \times 10^5 \tag{1}$$

3.2 Model Fabrication and Experiment Setup

Previously mentioned 2 W 40 mm diameter aluminium cone speakers were used. The model was made using simple hand-held cutting tools and epoxy to join the components together. The design features included two speakers at each end of the steel cylindrical tube with 1 mm slit along its length. The diameter of the steel tube matched the diameter of the speakers. By blocking the two ends of the steel tube with the speakers, no sound energy was able to escape except through the slits. The sound energy was to exit through the slit and interacted directly with the turbulent air flowing over the model wing. The slit was located at 0.23c from the leading edge. To mount the model on the test bench, a 0.5 inch stainless steel tube was inserted through the span wise direction of the model.

The experiment was carried out by placing tufts over the wing. This was to observe the flow properties over the wing and to visually make comparison between the excited and non-excited condition. The wing was set at an angle just before it stalled (α_{stall} was 18^o). Then the acoustic excitation was activated. The α was then increased to pass its non-excited stall angle of attack. Through the motions of tufts the flow characteristics over the wing were visually determined between the excited and non-excited condition.

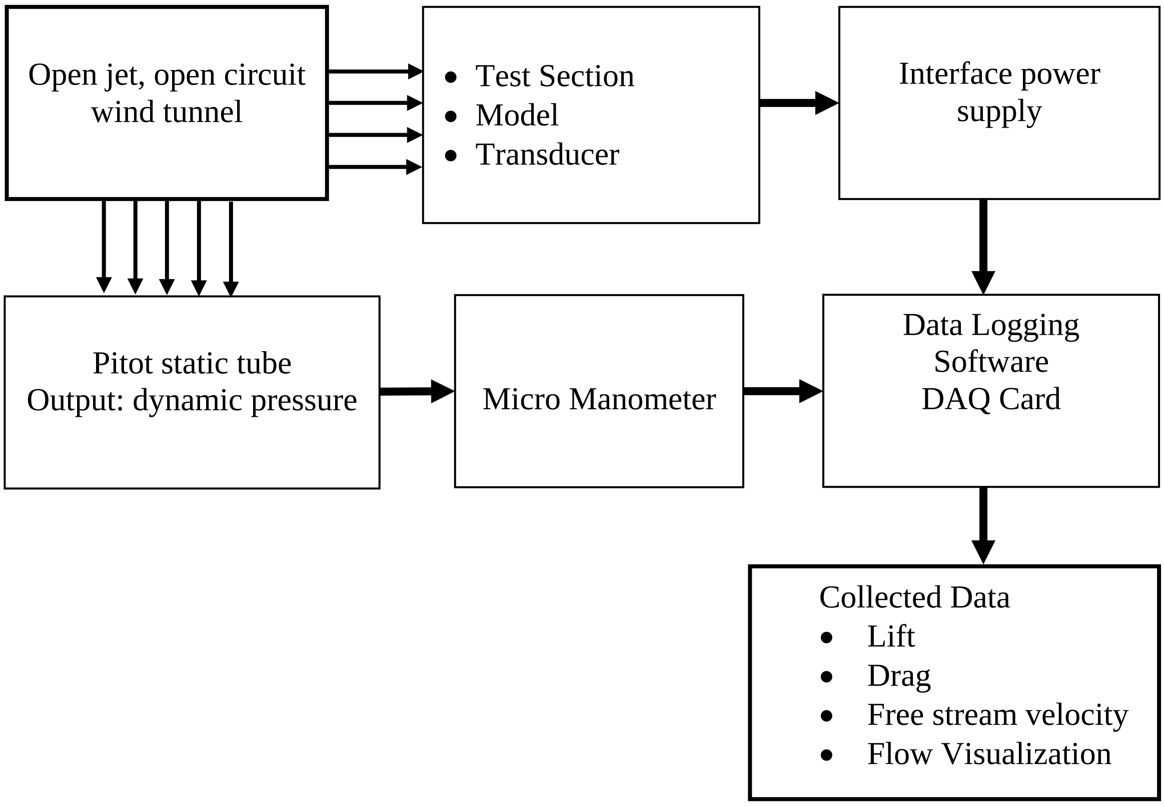

Figure 2 - Schematic diagram of the Open jet wind tunnel setup

3.3 Results from the open-jet open circuit subsonic wind tunnel experiment

When speakers were on, the size of the region of turbulence was reduced and delay in the stall angle was found. Table 1 below outlines the finding.

Table 1 - Summary of flow visualization experiment at 7 m/s (R_e = 1.22 x 10^5)

α (deg)	**Beginning of partial flow attachment excitation frequency**	**Maximum flow attachment excitation frequency**
19.0^o	116 Hz	700 Hz
19.5^o	300 Hz	1000 Hz
20.0^o	550 Hz	815 Hz
20.5^o	800 Hz	1100 Hz
21.0^o	900 Hz	1086 Hz
21.5^o	1036 Hz	

3.3.1 Result at: $U_\infty = 7$ m/s ($R_e = 1.22 \times 10^5$) at $\alpha = 19^o$

Flow started to re-attach at f_e of 116 Hz and remained attached until 700 Hz. The motion of the tufts showed clear distinction between the turbulent and laminar flow during the excited and non-excited stage. The important observation made during this stage was the ability of the acoustic energy to "remove" the turbulent flow instantly when the excitation was activated. That is, the initial properties of the flow over the wing did not have to be a laminar for the flow to re-attach. By switching the speakers on and off, the transition from the turbulent to laminar flow over the wing was possible. The acoustic excitation energy was strong enough to energize the low momentum boundary layer to impose the reattachment and therefore delay the stall angle.

3.3.2 Result at: $U_\infty = 7$ m/s ($R_e = 1.22 \times 10^5$) at $\alpha = 19.5$ to 21.0^o

With no excitation at $\alpha = 19.5^o$, the wing was stalled. The tufts oscillated violently indicating the turbulent flow on all parts of the wing. When f_e was set at 300Hz, the flow started to attach and continued to remain attached up to 1000 Hz. However, unlike the previous case, in order to reduce the turbulent flow at $\alpha = 19.5^o$ with f_e of 300 Hz the flow had to be laminar at lower α over the lifting body. That is, to observe the laminar flow and to delay the α_{stall}, the f_e had to be set at 300 Hz when $\alpha = 18.5^o$, then increase to 19.5^o. This phenomenon was different from the previous case, where the acoustic excitation was able to force the turbulent flow over the wing to transit back to the laminar flow. The finding showed two separate purposes for acoustic means of excitation. The first function was to prevent separation and the second function was to impose re-attachment by acoustic means. Clearly this condition worked to prevent flow separation rather than impose re-attachment. The flow had to be a laminar at low angles of attack before any improvement, with excitation on, was seen at high α. The maximum flow attachment over the wing occurred at f_e between 700 Hz to 800 Hz. Once acoustic excitation was turned off, tufts oscillated violently, clearly indicating the improvement gained from the acoustic excitation.

3.3.3 Result at: $U_\infty = 7$ m/s ($R_e = 1.22 \times 10^5$) at $\alpha = 21.5^o$

Slight improvement was seen at 1036 Hz where partial flow attachment was observed. For any α higher than 21.5^o, the flow over the wing degraded for all excitation frequencies. Even the slightest change in flow speed or variation in f_e during the excitation mode tripped the flow from laminar to turbulent.

3.4 The Shedding Frequency and Excitation Frequency

The excitation method most similar to this study was done by Liu & Shyu and Chang (1990) [8], Hsiao & Shyu (1992) [4] where they used an audio speaker and a slot to excite the flow. They found in their study that, if the natural vortex shedding frequency (f_s) matched closely to the f_e then the lifting surface showed optimum result. Therefore, using the method devised by Roshko (1954) [10], the theoretical shedding frequency was calculated. Further comparison between the natural vortex shedding frequency (theoretical result) and the excitation frequency (experimental result) are discussed below.

$$St_{\sin\alpha} = \frac{f_s c \sin\alpha}{U_\infty} = 0.17 - 0.19 \qquad (2)$$

The parameters are c = 255 mm, $\alpha_{stall} = 19^o$ and u_∞ = 7 m/s and therefore range of f_s were:

$$f_{s(\max)} = \frac{U_\infty}{c \times \sin\alpha \times 0.17} = \frac{7}{0.255 \times \sin 19^o \times 0.17} = 496\,\text{Hz} \tag{3}$$

$$f_{s(mix)} = \frac{U_\infty}{c \times \sin\alpha \times 0.17} = \frac{7}{0.255 \times \sin 19^o \times 0.19} = 443\,\text{Hz} \tag{4}$$

The range for f_s based on measured stall angle and free stream velocity was between 400 Hz and 500 Hz range.

Going back to Table 1 and the flow visualization experiment, between α = 19 and 20^o, 400 Hz to 500 Hz were within the range when flow reattachment was observed over the wing. The experimental result was similar to Change, Hsiao and Shyu (1992) [4], and it can be concluded that correlation between the vortex shedding frequency and optimum excitation frequency had been further proven to be an effective measure of finding the optimum internal acoustic excitation frequency.

For angles of attack ranging from 20.5^o to 21.5^o higher f_e were required to affect the flow over the wing. This phenomenon cannot be explained by natural vortex shedding frequency and Strouhal number. Zaman et al. (1987) [14] also observed similar effects where higher frequencies range around 500 Hz to 1500 Hz were required for high angles of attack. Possible reasons for higher frequencies may be due to resonant affect or the first fundamental harmony frequency. Further, location of acoustic excitation as well as speed of the ejecting sound energy from the slit may have contributed to difference between f_e and f_s for cases at high angles of attack.

3.5 The Excitation Frequency Speed

The velocities of the sound energy emitted from the speakers were measured using a hotwire. The velocities emitted from each speaker, corresponding to excited frequencies, are graphed in Figure 3. The aim was to find a relationship between the speeds of the emitting sound energy and optimum f_e.

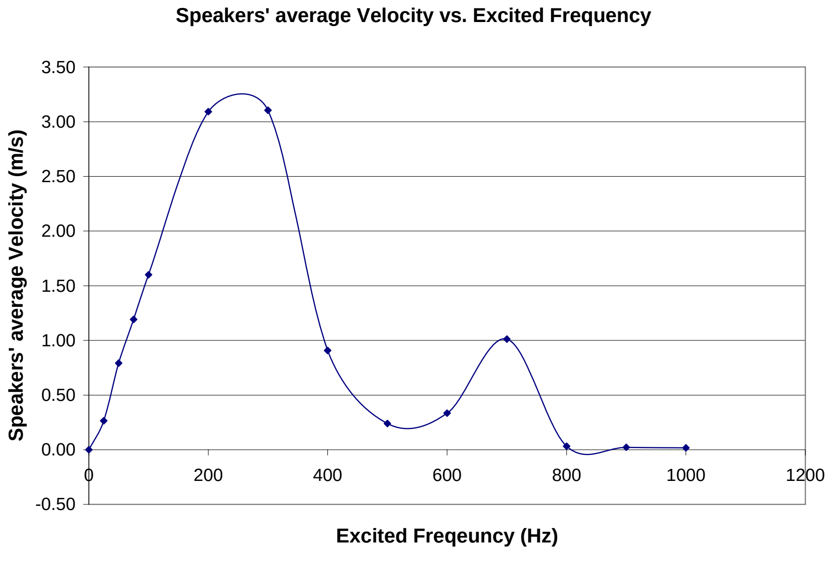

Figure 3 - Speakers' average emitting velocity vs. Excited Frequency

Figure 3 depicts two f_e peaks, between 200 Hz to 300 Hz and at 700 Hz. These f_e, at which maximum speakers' average velocity were found corresponded to maximum flow attachments obtained during the experiment. Therefore the relationship exists between the velocities emitted from the four speakers' and the amount of flow reattachment over the lifting surface. However, for flow attachment that occurred at f_e greater than 800 Hz (as stated in Table 1), it was possible that the flow was energized during the lower f_e range and only a small energy was all that was required for flow to attach and remain attached at higher f_e.

3.6 The Strouhal Number

With the results obtained from the flow visualization experiment, it was clear that the effectiveness of boundary layer control was highly sensitive to the excitation frequency (also observed by Hsiao, Liu and Shyu et al.1990 [8]). How flow properties correlate with the excitation frequency was a very important problem in this study and can be explained by Strouhal number. The Strouhal number (Sr) is a governing non-dimensional number that relates the excitation frequency to the chord length and the free stream velocity.

$$Sr = \frac{f_e C}{U_\infty} \tag{5}$$

From Table 1, at $\alpha = 20^o$, the frequency ranged from 550 Hz to 815 Hz. This gives a Sr range of:

$$Sr = \frac{f_e \times 0.255}{7} = 20 - 30 \tag{6}$$

The calculated range of Sr = 20-30 was well within the range mentioned by Ahmed and Archer (2001) [1]. Ahmed and Archer et al. found that at $R_e = 1.0 \times 10^5$, Sr was between 22 and 40. From the analysis, it was concluded that the current design matched closely to the previously found Sr numbers from the earlier studies. For the Sr, the range between 20 to 30 gave most, if not the maximum, flow attachment during the acoustic excitation period for this concept.

4. CONCLUSIONS

The study of the internal acoustic excitation to control and improve the flow separation over an airfoil was conducted in a smoke laminar wind tunnel and in an open-type subsonic wind tunnel. Results from the smoke laminar wind tunnel experiment showed that a lifting body when excited by acoustic means can reduce flow separation and delay stall angle. It was proven that the method of acoustic implementation was promising and effective in reducing the separation and consequently improving the aerodynamic performance in the post stalled region. In the post stalled region, the stall angle had been delayed by up to 2.5 degrees in the present set up at a Reynolds number equal to 1.22×10^5. It was clear that the current internal excitation technique improved the flow characteristics over the wing and showed significant potential.

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