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A BRIEF REVIEW ON VARIOUS NOISE REDUCTION TECHNIQUES EMANATING FROM WINGS OF AN AIRCRAFT

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Abstract— **One of the challenges and a point of need in the aviation industry is the problem of high level of noise emanation. There are various sources of noise emanating from aircraft which are the noises from engine and airframe including the wings. Noise from the wing is an important phenomenon to be put into consideration as it contributes significantly to the noise emanating from aircraft especially during take-off and landing. Airfoil noise emission emanate on the wing section of an aircraft due to the interaction of the airfoil turbulent boundary layer with the sharp leading edge. Noise reduction then becomes a thing of concern for many engineers and researchers who took it upon their shoulder the responsibility of coming up with design that can help reduce noise emanating from aircrafts to mitigate the noise. Due to this, many researchers have focused on reducing the noise emanating from the aircraft through various means and approaches which include theoretical, computational, and experimental analysis. In a means of compiling and making available a brief review of such work, for easy and quick access necessitate the need of this work. This paper focused on giving a summary and review of different work done by past and current researchers in the field. The review was based on selected current papers on the cutting-edge technology towards enhancing aerodynamic performance of the wing of aircraft and reduction of noise emanating from it. Although fruitful results have been achieved in the aerodynamic noise control, but only little work has been done to summarize the main findings and progresses in this area. This work focused on review of work carried out by many researchers in this area which involves various techniques and attempts ranging from leading edge serration, trailing edge serration, active flow actuation, flexible wing using theoretical, computational, and experimental approach etc. Additionally, some suggestions were made towards further study and improvement in this field of study.**

Keywords— **Trailing Edge Serration, Leading Edge Serration, Leading Edge High Lift Devices, Aerodynamic Performance**

I. INTRODUCTION

The aviation transport industry keeps growing and likewise the population of people around the world keeps growing and of such buildings have keep growing even around major airports. Most airports around the world now are being surrounded by many households who live around the airports. Airport transportation management were left with no choice but to make policy that will make airport environment and surrounding conducive for living. This necessitates a policy that was geared towards reducing the noise coming from the airport activities. Noise reduction then becomes a thing of concern for many engineers and researchers who took it upon their shoulder the responsibility of coming up with design that can help reduce noise emanating from aircrafts so as to mitigate the noise. This paper is based on many research and findings of various researchers towards solving the noise coming out from aircraft wings and also towards improvement of aerodynamics performance.

Noises from aircrafts come from two major sources which are the engine and the airframe [1, 2]. This review is limited to various work geared towards reduction of noise generated in the aircraft wing which is a part of airframe of an aircraft. Airfoil noise emission emanates from the wing section of an aircraft due to the interaction of the airfoil turbulent boundary layer with the sharp leading edge [3] and vortex action on trailing edge. Various techniques have been developed towards the mitigation of noise coming from this source through various approaches such as carrying out some theoretical evaluation, computational and experimental method. Some of the techniques include the introduction of serrations on the leading edge and trailing edge, use of active flow control, flexible wing structure etc. Many of the techniques are bio inspired by studying the silence flight of an owl bird [15, 18]. Many researchers tried to mimic and make a mechanism that can function like the feathers or wings of owl bird. Basically, in the past, two major techniques were employed which can be categorized into two which were the active and passive techniques [10-13]. The active techniques involve the addition of devices such as actuator which by using some energy as input manipulate the flow around them. The passive technique involves changing or altering the geometry of airfoil in such a way to reduce the effect causing noise generation [8, 9]. The limitation in this approach inspired researchers to learn from the silent flight of owl bird. This bio inspired noise control technique is surely one of the promising techniques. This work focused on review of such work carried out by many researchers in this area involving various techniques and attempts made ranging from leading edge serration, trailing edge serration, active flow actuation, flexible wing with the method of approach used including theoretical, computational, and experimental approach. Additionally, some suggestions were made towards further study and improvement in this field of study.

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1.1 Trailing Edge Serration Technology

Airfoil noise emission emanate on the wing section of an aircraft due to the interaction of the airfoil turbulent boundary layer with the sharp leading edge [16, 2]. This noise has been confirmed to be effectively reduced by using trailing edge serration [3]. This had been proven analytically and experimentally by a wide range of scientists whose works are listed in the reference of this paper.

A computational study of effect of trailing edge of flat wing, wavy serration and saw tooth serration on airfoil noise instability using a simplified approach based on equation proposed by Howe, 1991 was used by Visalatchi and Sugades. They used NACA 0018 airfoil with trailing edge serration in a low to moderate speed flow under acoustical free field conditions. ANSYS FLUENT was used to analyze the airfoil. Finite Element analysis (FEA) software was used for acoustic measurement and to study the mean topology and turbulence statistics of the flow near trailing edge serration [3]. The saw tooth serration have sharp edges while wavy serration have curve edges. A study on flat trailing edge without serration and trailing edge with wavy serration and also that with saw tooth serrations were considered. The results gotten revealed a more reduction in the noise emanating from a trailing edge with wavy serration, followed by saw tooth serration and more noise emanating from flat trailing edge than others. It was also discovered that a broadband noise reduction can be achieved with saw tooth serration of trailing edge with flat plate configuration in a real-life application [3].

AVallone, Velden et al carried out a computational analysis on NACA 0018 airfoil same airfoil used by [3] at zero angle of attack by solving the explicit, transient, compressible lattice Boltzmann equation while the acoustic far field was obtained by means of the Ffowc Williams and Hawking analogy [13]. The numerical results were validated against experimental results. The study reflected that combed saw tooth serration reduced more noise than the conventional saw tooth. The presence of combs affected the intensity of the scattered noise but not the frequency range of noise reduction. Thus, there is a need to find a means of not just reducing the intensity of scattered noise but to be able to reduce the frequency range of the noise. This also showed that the installation of combs mitigate the interaction between the two sides of airfoil at the trailing edge and the generation of a turbulent wake in the empty space between the teeth [13].

The study by Avallone et al acts as an improvement on the work by Visalatchi et al on the computational acoustic analysis on trailing edge of serration wing for reducing instability noise. The work done by Visalatchi et al showed an option of achieving further noise reduction of saw tooth serration trailing edge by the application of a more flat trailing edge(with saw tooth serration) while the study by Avallone provide another option of introducing a combed saw tooth serration. Combining these two options is likely to produce a better result.

In their study, Renato, William et al proposed a technique to compute the aeroacoustics transfer function by allowing the study of the leading-edge noise radiated by realistic airfoil geometries. This method accounted for trailing edge aerodynamic back- effects scattering and is valid for blades with large spans, general airfoil geometries, high frequency perturbation and subsonic compressible fluid [4]. The technique dealt with the possibility of rewriting the linearized potential flow equation as Helmholtz formulation leading to a boundary value problem prescribed by the linearized airfoil theory [4]. A method of iterative procedure was done by using a boundary element method (BEM). This was verified using Amiet's theory. Amiet theory presented a formulation where the airfoil response to a high frequency incoming periodic perturbation is computed by the solution of Helmholtz equation using Schwarzschild technique.

The paper presented a numerical framework to compute the compressible aeroacoustic transfer functions of realistic airfoils. Amiet's solution was obtained numerically by using Boundary element method (BEM). The solution of Helmholtz equation was obtained by BEM through the use of Schwarzschild technique. This method after validating with analytical solution, it was then applied to the boundary conditions representing realistic airfoil configuration [4].

In summary, a comparison of BEM solution of a flat plate with analytical solution was carried out and then the behavior of the solution under a more realistic airfoil configuration was evaluated. The acoustic scattering from realistic airfoils subjected to an unsteady gust was presented for a suit of NACA four digits airfoil profile [4]. It was observed that thicker airfoils have low amplitude in terms of chord-wide pressure fluctuation distribution and are expected to radiate low far-field noise due to gust leading edge impingement. Camber effect was shown not to have a great influence on the aeroacoustics transfer function [4].

Boundary Element Method (BEM) was employed to compute the unsteady load distribution of an airfoil subjected to a high frequency turbulent stream using Amiet's theory [4]. Two iterations of Schwarzschild problem were performed with BEM to compute both the leading and trailing edge corrections [4]. This made it possible to converge the solution of high frequencies. It was demonstrated from the results gotten that the amplitude of the aeroacoustics transfer functions were reduced for the thicker airfoil but the camber effect does not show a great impact on the leading and trailing edge corrections for pressure distributions along the airfoil. Higher free stream Mach numbers and oblique gusts lead to larger load distributions of pressure fluctuation along the airfoil while keeping K1 constant [4]. The numerical solution did not fully prescribe what is gotten analytically when an oblique gust was employed.

In a study by Visalatchi et al [3], it was proposed that having a sawtooth serration trailing edge on a flat plate will cause more reduction in the noise level than just a trailing edge with sawtooth serrations. This suggestion by Visalatchi can be said to form the basis of the work carried out by Danielle, Laura etal in their paper titled ‘Flat Plate Self Noise Reduction at Low to Moderate Reynolds Number with Trailing Edge Serrations’ They carried out an experimental measurement in which flat plate with both sharp and serrated trailing edge were studied in an anechoic wind tunnel.

Trailing edge serrations are believed to reduce the radiated noise by minimizing the effective span wise length of trailing edge that contribute to noise generation [5, 23]. In their study, acoustic test was conducted on a NACA 0012 airfoil at a various angle of attack and Reynolds number ranging between 1x10^5 and 5x10^5. Trailing edge serrations were found to eradicate flow separation close to the trailing edge and in turned lowered the amplitude of the broadband and tonal noise components. Larger reduction in the tonal noise components were achieved with larger serration angle between the mean flow and local target to the wetted surface [5]. A comparison between straight unserrated configuration and that with serrations with two different serrations geometries of wavelength 3mm (narrowed serration) and that of wavelength 9mm (wide serration) were considered [5]. The serrations in both cases had root-to-tip amplitude of 2h=300mm.The experiment were carried out at a various speed of flow between U=7 and 38m/s. It was observed that at flow speed below 12m/s, the noise levels at low frequencies were observed to increase in amplitude with decreasing flow speed and reach peak at 9m/s and then in reduce in amplitude with further decreasing in flow speed while at a speed between u= 15 and 38m/s there is a clear trend with noise level reducing with a decrease in in flow speed [5]. Their findings also revealed that at u=38m/s the noise level of all the three plates were approximately equal at a frequency below 5kHz while above this frequency, trailing edge serrations produced a region of noise attenuation. The noise attenuation was shown to reduce in frequency and amplitude with decreasing flow speed to u=15m/s. The two serrations almost have the same performance but that with wide serrations achieving just slightly higher levels of noise attenuation than the narrow ones.

Due to vortex shedding from narrow serrations between u=9 and 12m/s, a noise increased was produced at low frequencies and a few broad, high amplitude peaks were recorded in the noise spectra [5]. Above the peak frequencies, the narrow serrations perform similarly to the wide ones at all frequencies considered in their investigation. The wide serrations were observed to produce higher levels of attenuation over a larger frequency range at all flow speeds between U= 7 and 12m/s.

The measured noise reduction were found to occur over a certain Strouhal number range with attenuation being achieved between St=0.7 and St=1.4 at high flow speed with 1.7x10^5<Re_c <4.5x10^5 and at St<0.7 at low flow speeds with Re_c<1.7x10^5. Contrary to Howe (1991b) theory, serrations with larger wavelength to amplitude ratio were found to achieve higher attenuation levels. Detailed flow field measurements around the trailing edge region were not considered in this study and could be another step towards a further investigation by the authors.

Mathieu Gruber et al compared the measurements of trailing edge self-noise reduction of sawtooth and slit serration of a NACA 651210 airfoil. A detailed experiment work was conducted in the ISVR’s open jet wind tunnel. It was reported that a noise reduction of about 5dB over a large frequency was achieved by the introduction of serrations on trailing edge [6]. Sawtooth and slit geometries were considered with angle of attack being 5^0 and the boundary layer was tripped so as to birth turbulent. Static pressure coefficient distributions along the chord of airfoil were reported. The paper was aimed at comparing noise radiation predicted by Howe’s theory for sawtooth serration and Howe’s extended theory for slit serrations against experimental data [6]. The target goal of Mathieu et al was to reduce the broadband noise generated by the turbulent boundary layers by using passive treatment such as sawtooth and other trailing edge geometries on NACA 6512-10 airfoil. The noise data for mean flow velocities of 20, 40, 60 and 80m/s for five geometrical angles of attacks; -5, 0, 5, 10 and 15^0 were taken thereby making five sawtooth and four slitted geometries results that were taken [6].

Noise reduction were predicted at 90^0 overhead of the trailing edge for a mean flow of velocity 40m/s and a measured turbulent boundary layer thickness of 7.1 mm for the straight edge and 8.0mm for serration at 5^0 angle of attack of the airfoil [6]. It was observed that slit serrations are not effective noise reduction treatment since noise reduction asymptotes to zero at high frequencies [6]. The introduction of obliqueness of edge relative to the flow direction by the sawtooth was suggested to be one of the reasons for the high noise reduction potential in the high frequency region.

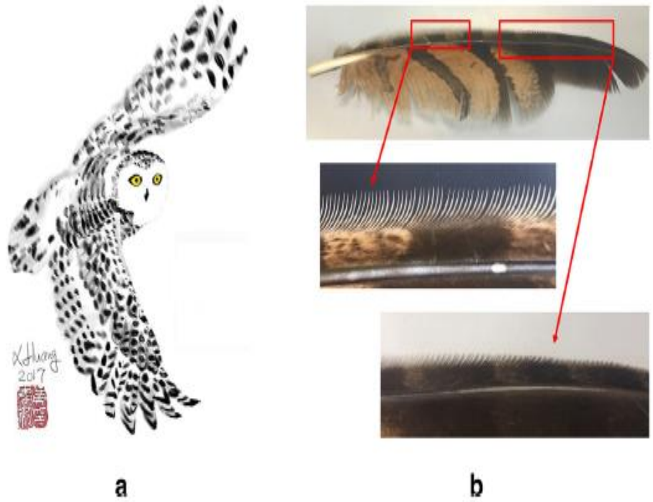
The comparison of their experimental results and previous experimental studies with that of Howe’s theory does not agree as it was shown that Howe over predict considerably the noise reduction achieved in practice [6]. It was recorded that the greatest noise reduction measure was about 5dB for sawtooth while 1dB for slitted serrations. It was reported that sawtooth trailing edge gives a noise reduction from frequency of 300Hz to 7kHz while in slitted serration, the noise was increased by 1-2dB in this frequency range [6]. It was suggested that the mechanism by which radiated noise are being reduced are not yet fully understood. Mathieu et al, proved that such radiation as proposed by Howe cannot be achieved and suggested that other mechanism of noise generation are also involved and dominant. The limitation of the study is that the effects of serrated edges in the trailing region were not estimated because there was no static pressure sensor close to the trailing edge when the experiment was being carried out.

One of the proven valid applications of reducing trailing edge noise is by serration of trailing edges of an airfoil [11]. Computational approach by using large-eddy simulation (LES) and Lighthill-Curle Method were employed to reveal the variation in the hydrodynamic field and sound source due to trailing edge serrations [11]. They discovered that the trailing edge serrations inhibit the growth of spanwise vortices and promote the development of streamwise vortices close to the trailing edge and wake. A reduction in the velocity in the vertical cross section of the streamwise direction close to the trailing edge was observed which reduced the local peak value of sound pressure [11]. The simulation was carried on a NACA 0012 airfoil. Hui Tang et al findings support the fact that applying serrations on the upstream of the reattachment point reduces the trailing edge noise.

Hui Tang et al showed the variation in the hydrodynamic field caused by trailing edge serrations found the relation between the hydrodynamic field characteristics and noise reduction. It was confirmed that the growth of the spanwise vortices near the trailing edge is impeded by the trailing edge serrations as discussed by Hui Tang et al. The trailing edge serration was observed to cause an increase in drag on the airfoil though they prevent the growth of spanwise vortices near the trailing edge [11]. Trailing edge serration was confirmed to decrease the distribution of sound waves near the trailing edge. Thus, applying serrations on upstream of the reattachment point of an airfoil was proven to be effective in terms of noise reduction [11]. Physical noise reduction mechanism has not yet been adequately studied.

1.2 Leading Edge Serration Technology

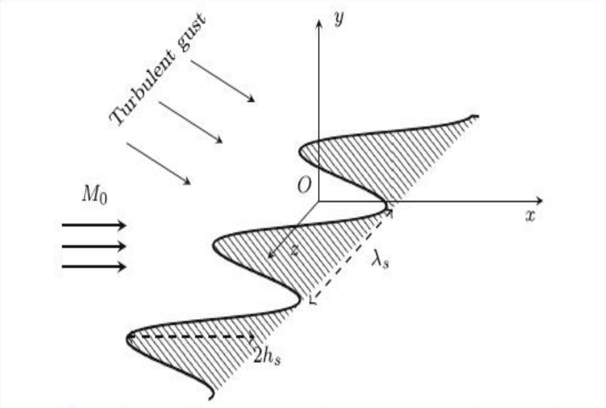
Airfoil–turbulence interaction is one of the dominant broadbands of flow-induced noise generation in aircraft and other fluid turbomachinery [16]. In order to solve this problem, many researchers have opened up to the technology of applying serration on the leading edge of aircraft which is a promising approach to reduce the noise developed on the aircraft wing. Huang (2019) focused on this promising technology with a theoretical approach and proposed an analytical model by incorporating Fourier transform into the Wiener–Hopf method to study of serrated leading edges in airfoil and vertical gust interaction noise. The proposed model suggested that the serrations operate on the incident vertical gusts as convolution, which leads to the innovative concept that model serrations as transfer functions in the wavenumber domain [16]. The serration approach has a presumed connection to the silent flying capability of owls [17–19] and, as shown in Fig. 1, the primary feather from an owl actually contains very long, curved and comb-like leading- and trailing edge serrations, which demands further studies of shape optimizations and modeling capabilities [16].



The problem of interest, where **(a)** the sketch of a flying snowy owl, and **(b)** one of the primary feathers from an eagle owl and the corresponding leading-edge image

Fig. 1 Credit to Xun Huang [16]

Overall, many recent works from various groups and universities such as Brunel University and Southampton University, have performed a series of pioneering experimental studies of airfoil aerodynamic noise with serrations in realistic set-ups, which have provided sufficient physical insights that shall further enable the follow-up theoretical studies [16]. Then, the main focus of the work carried out by Huang [2019] was to theoretically develop an analytical model for the scattered sound waves from an infinitely thin airfoil with serrated leading edge in the presence of a uniform background flow. The work by Huang [2019] utilized Fourier transform to establish the closed form solution and, from which, proposed a transfer function in the chordwise–spanwise wavenumber domain to clearly elucidate the possible noise control effect of the serrations.



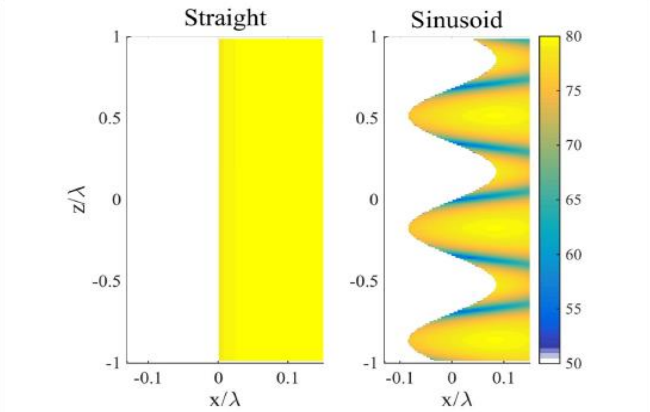
Sketch of the model problem, where the (sinusoidal-shaped) wavy serrations with the profile $\chi(z)$ (with amplitude $2h_s$ and the wavelength λ_s) are shown as an example. We wish to mention that our model also works for other shapes, such as sawtooth- and slotted-shaped profiles

Fig. 2 Credit to Xun Huang [16]

The transfer function for serrations was defined by Huang [2019] as.

$$S(\alpha,\beta)=\frac{\sum_{\kappa=-\infty}^{+\infty} s^{[\kappa]}(\alpha)A_g\left(\beta-\kappa\frac{2\pi}{\lambda_s}\right)}{A_g(\beta)}=\frac{\sum_{\kappa=-\infty}^{+\infty} s^{[\kappa]}(\alpha)\delta\left(\beta-\kappa\frac{2\pi}{\lambda_s}\right)*A_g(\beta)}{\delta(\beta)*A_g(\beta)},$$

This clearly elucidated the noise control effect of the serrations and showed that serrations operate on incident gusts (or more generally, turbulence flows) in the form of convolution [16]. The model by Huang [2019] employed the frozen turbulence assumption and semi-infinite thin airfoil in the presence of uniform flows at zero angle of attack. It is well known that frozen turbulence assumption is usually valid for uniform or weak sheared flows. The semi-infinite airfoil assumption should be valid for high-frequency gusts [16].



The predicted sound pressure levels (in dB) of the scattered sound field on the upper surface at $y=0^+$, where the vertical axis shows the spanwise coordinate and the horizontal axis shows the streamwise coordinate. Both coordinates are normalised by the sound wavelength at the frequency. The other set-ups are the same as those in Fig. 6

Fig. 3 Credit to Xun Huang (16)

"The proposed model shall enable one to rapidly study the noise reduction performance of various-shaped (and even aperiodic) serrations for different incident vortical gusts" [Huang, 2019]. It is worth noting that the model proposed by Huang [2019] is limited to frozen turbulence assumption and semi-infinite thin airfoil in the presence of uniform flows at zero angle of attack which is valid for uniform or weak sheared flows and high-frequency gusts.

1.3 Leading Edge High Lift Devices Technology

The recent technology claims the fact that the introduction of high bypass ratio engines had significantly reduced noise coming from the engines in the recent technology [5, 7]. Now, more focus is on the frame which includes the wings and its addendum e.g., flaps. Slotted devices on the leading edges produce high noise because of the recirculation that develops in the core region [7, 20-22]. This technique revealed a process by which this can be mitigated. Many researchers have demonstrated the effectiveness of slat core fillers in reducing the level of noise caused by slotted leading edges by using various tools which are computational analyses, wind tunnel experiments and up to full scale flight test [7].

Properly designed slat fillers had been demonstrated by Boeing computationally and corroborated in experiment campaign to potentially enhanced airplane performance and lower noise generation [7]. Study on extending slat cove filler other leading-edge devices like Krueger flaps which is commonly use in this era was carried out by Arvin S. and Eric Dickey in 2020. Slotted slats are incompatible with laminar flow because of pane gap between slat and main wing when the slats retracted while Krueger is suitable for laminar flow because when mounted on the lower side of the wing, the upper surface remains continuous [7]. The work of Arvin and Dickey was to identify promising Krueger flap fillers and the development of cove fillers for various Krueger flaps with the purpose of enhancing the aerodynamic performance and reduction of noise generated in the leading edge of aircraft wings. Extensive studies on the three main Krueger flap variant were carried out with results not too good as when compared with slotted slat. It was noted that none of the Krueger flaps achieved maximum lift at landing when compared to slotted slat. Thus, a need for optimization of Krueger variant in the future for a higher maximum lift as it was already proved with the optimization of camber Krueger flap with a maximum lift of about 4.25 comparable to slat and with a milder drop in lift at higher angles of attack [7].

The cove fillers for respective Krueger variant for improved lift to drag ratio performance followed a design procedure that aims at minimizing aerodynamic losses [7]. The fillers were designed to improve the quality in the channel between Krueger flap and the wing. In all cases, the solution revealed that Krueger-fillers outrightly eliminate flow separation and prevent the formation of wake on their edges.

The flow recirculation and trailing wake that originate at the edge of the flap contribute to the noise of the baseline Krueger flaps [7]. The introduction of filler was shown to avert flow recirculation and rendering a streamlined flow in the slot region. The wake of the lower edge was completely eliminated with fewer wakes at the upper edge. Thus, the total pressure profile across the remaining wake is particularly effective in suppressing this noise source [7].

Computational simulation was used to guide the development of Krueger-Filler shapes for a chosen wing section. The filler was shown to improved channel flow and reduce both the width and intensity of wake off of the filler which improve the aerodynamic and acoustic characteristics of the wing. The fillers are effective in reducing the noise of gapped leading-edge devices which is not only limited to improve flow quality but also to conceal linkages, levers and actuators needed for deploying the Krueger element [7].

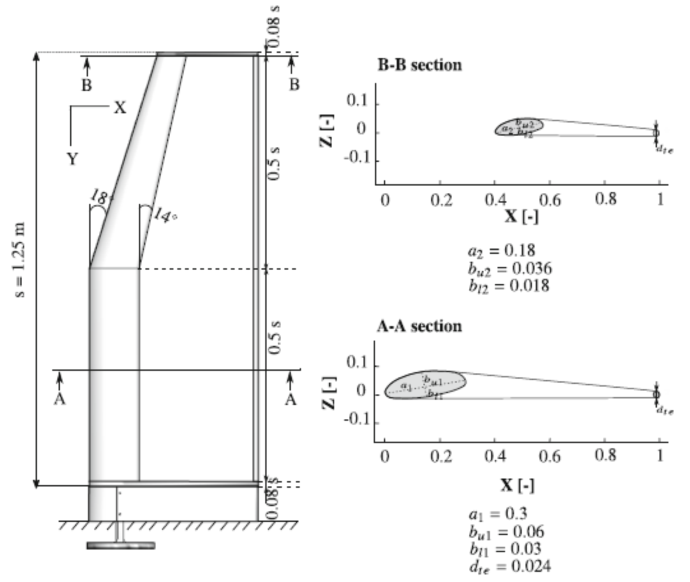
Major emphasis and analyses were done on the attached element of the wing without considering the full wing configuration. There is therefore, a need to assess the Krueger-Filler with respect to full wing configuration. There is also a need for further experimental investigation on the results, the feasibility and ease of application of this technique on aircraft without causing another major point of concerns. The major setback has to do with complexity of mechanical system that solves the problem of integrating slat cove fillers.

Finally, this technique has a future impact on airplane performance, fuel economy and environmental impact if further study can be made. A further study on geometries optimization and experimental validation is necessary to take this technique to higher level of aviation application.

1.4 Brief about Flexible wing/Morphing wing

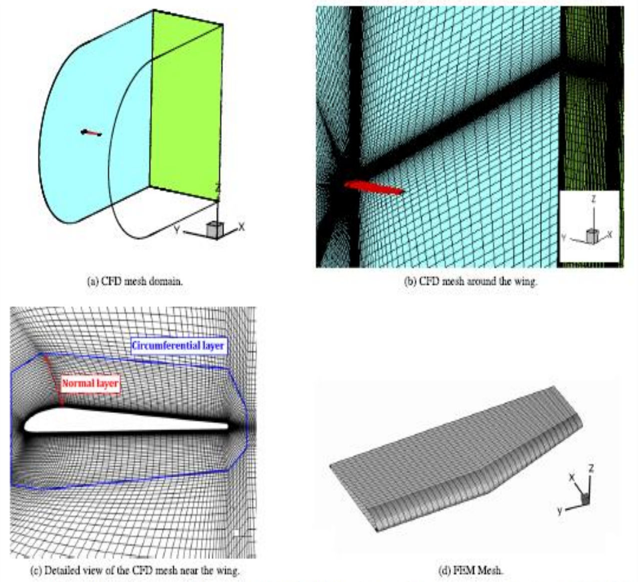
Piquee et al investigated three-dimensional membrane type wings by applying fluid-structure-interaction computations and complementary experiments. Analyses for three Reynolds numbers were conducted at various angles of attack computationally using TAU-Code and the FEM Carat++ solver [15]. An experimental wind tunnel tests were performed for performance analysis and to estimate the accuracy of the computations. In the results, the advantages of an elasto-flexible-lifting-surface concept were highlighted by comparing the form variable surface to its rigid counterpart [15]. The adaptation and flexibility of the material to the freestream allow the membrane to adjust its shape in response to the pressure distribution [24]. For positive angles of attack, the airfoil's camber increases resulting in an increase in the wing lifting capacity.

Furthermore, the stall onset was postponed to higher angles of attack and the abrupt decrease in the lift was replaced by a gradual loss of it [15]. Morphing aircraft are able to transform their configuration by using shape-adaptive systems. They can refer to a change in the outer shape or in the inner structure, and it can involve a change in the noise and the electromagnetic signature [15, 25]. The main purpose of such a system is to increase flight efficiency and expand flight envelopes (using a single aircraft can be used for various types of missions), [15, 24]. Piquee et al presented a Fluid-Structure interaction (FSI) investigation of an elasto-flexible membrane wing/airfoil. The Reynolds averaged-Navier-Stokes (RANS) code TAU from the German Aerospace Center (DLR) and the finite element method (FEM) CARAT++ from the Chair of Structural Analysis at Technical University of Munich (TUM-SA) were employed. Comparison with experimental data was done to evaluate the validity of the computations, and eventually leads to an assessment of the passive-camber-change concept.



Three dimensional elasto-flexible membrane wing model with geometrical characteristics

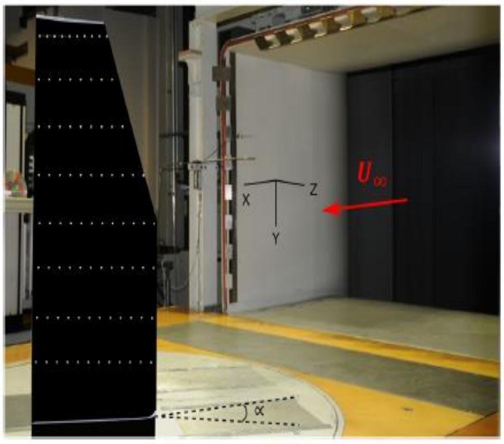
Fig. 4 Credit to Piquee et al, [15]



(a) CFD mesh domain. (b) CFD mesh around the wing. (c) Detailed view of the CFD mesh near the wing. (d) FEM Mesh.

CFD and FEM Meshes. **a** CFD mesh domain. **b** CFD mesh around the wing. **c** Detailed view of the CFD mesh near the wing. **d** FEM Mesh

Fig. 5 Credit to Piquee et al, [15]



Elasto-flexible membrane wing model mounted in the test section of wind tunnel A

Fig. 6 Credit to Piquee et al, [15]

The figures above showed the computational model and the experimental model with the two models having the same configuration. This was done so as to be able to compare both the computational and experimental results under same conditions and configuration. In the experimental analysis, stereo-photogrammetry technique was employed to measure the membrane deformation while an external six-components strain gauge balance is used to measure the aerodynamic forces and moments of the wing [15]. The table below shows their findings.

Table 1, Credit to Piquee et al, 15]

Summary of the different tests and measurement techniques

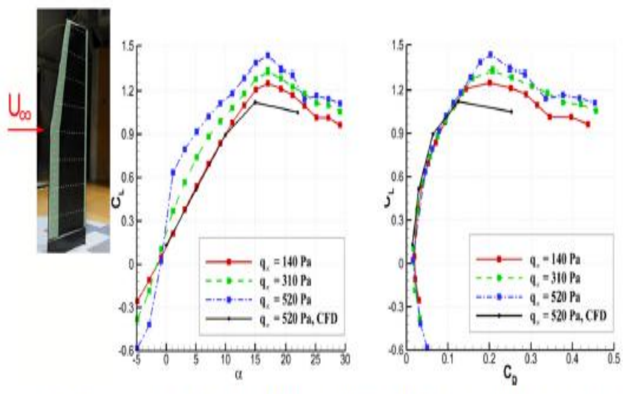
Flow condition	Force measurements	Deformation measurements
Re	$4.35 \times 10^5, 6.67 \times 10^5, 8.70 \times 10^5$	$4.35 \times 10^5, 6.67 \times 10^5, 8.70 \times 10^5$
q_∞	140 Pa, 310 Pa, 520 Pa	140 Pa, 310 Pa, 520 Pa
α	[-5 : 2 : 30] deg	-5 deg, 0 deg, 5 deg, 15 deg

Table 2, Credit to Piquee et al, (15)

Comparison of the lift and drag coefficients between the different spatial resolutions at $\alpha = 5$ deg and $\alpha = 10$ deg

-	Coarse	Medium	Fine
C_L at $\alpha = 5$ deg	0.519 ±0.027	0.516	0.515
C_D at $\alpha = 5$ deg	0.032 ±0.003	0.029	0.029
C_L at $\alpha = 10$ deg	0.906 ±0.026	0.898	0.897
C_D at $\alpha = 10$ deg	0.066 ±0.005	0.063	0.062

The FSI computations show a good agreement with the wind-tunnel data and shown below.



Evolution of C_L-α and C_L-C_D obtained with the experiments at three q_∞ and with CFD computations at $q_\infty = 520$ Pa

Fig.7 Credit to Piquee et al, [15]

The simulations were validated with wind tunnel data by a method of comparing the aerodynamic coefficients and the membrane deflection at various angles of attack. The wind-tunnel data were also performed for three distinct Reynolds numbers at various angles of attack. The aerodynamic coefficients were analyzed to draw conclusions about the dependency of the flexible geometry to the dynamic pressure [15]. The adaptation and flexibility of the material make a change of the wing geometry possible, which positively influence a lift increase. At small angles of attack, a positive membrane deflection and an increase in the airfoil's camber were observed [15].

II. SUMMARY TABLE

This table presents a brief summary of few of the papers consulted towards the writing of this paper.

Author(s)	Title	Year of Publication	Method of Approach	Conditions	Key Findings	Limitation	Technique	Airfoil Model used
F. Avallone, W. C. P van der Velden, D. Ragni and D Casalino	Noise Reduction Mechanisms of Sawtooth and Combed-sawtooth Trailing Edge Serrations	2018	Computational Method	At zero angle of attack	The studies confirmed that combed sawtooth serration reduced more noise than conventional sawtooth	The presence of combs only affects the intensity of the scattered noise and not the frequency range of noise reduction	Trailing Edge Serrations	NACA 0018

Mathieu Gruber, Mahdi Azarpeyand Philip F. Joseph	Airfoil Trailing Edge Noise Reduction by the Introduction of Sawtooth and Slitted Trailing Edge Geometries	2010	Experimental Method	At -5^0, 0^0, 5^0, 10^0 and 15^0 angle of attack, Mean flow velocities; 20, 40, 60 and 80m/s	It was recorded that the greatest noise reduction measure was obtained for ratio of wavelength to root-tip(periodicity)equal 0.3 or 5dB for the sawtooth trailing edge while for the slitted trailing edge, the greatest noise reduction is achieved when periodicity equal 0.1 or 1dB	The effect of serrated edges in the trailing region could not be estimated due to absence of pressure sensor close to the trailing edge when the experiment was carried out	Trailing Edge serration	NACA 6512
Danielle J. Moreau, Laura A. Brooks and Con J. Doolan	Flat Plate Self Noise Reduction at	2011	Experimental Method	At various angle of attack, 1x10^5 < Re < 5x10^5	Against the Howe theory, it was discovered that serration with larger wavelength to amplitude ratio achieved higher attenuation levels	It was limited to a single root-to-tip amplitude value	Trailing Edge Serration	NACA 0012

	Low to Moderate Reynolds Number with Trailing Edge Serrations							
Renato Fuzaro M., William Roberto W. and Leandro Dantas de Santana	Numerical Computation of Gust Aerodynamic Response to Realistic Airfo	2016	Theoretical Method	Realistic airfoil configuration	It was observed that thicker airfoils have a low amplitude in terms of chordwise pressure fluctuation distributions and are expected to radiate low far field noise due to gust leading edge impingement	The numerical solution did not fully prescribe what is gotten analytically when an oblique gust was employed	Leading Edge	Few NACA four digits airfoil

	ils: Application of Amiet's Theory							
Arvin Schmilovich and Eric Dickey	Leading Edge Devices for enhanced High-Lift and Reduced Noise	2020	Theoretical and Computational Method	Transonic wing with 11% thickness ratio, 8% long fixed Krueger flap and 26% trailing edge flap	It was discovered that the Krueger-filler significantly eliminate flow separation and prevent the formation of wake on their edges	No optimisation of Cove filler shapes were perform, the study only focus on identifying gross effects	Leading Edge	-
Xun Hang	A Theoretical Study of serrated Leading E	2019	Theoretical Method	Thin Airfoil of serrated and straight leading edge. Zero angle of attack.	The proposed model shall enable one to rapidly study the noise reduction performance of various-shaped (and even aperiodic) serrations for different incident vortical	It is worth noting that the model proposed by is limited to frozen turbulence assumption and semi-infinite thin aero foil in	Trailing Edge	-

	dges in aerofoil and Vortical Gust Interaction Nosie				gusts	the presence of uniform flows at zero angle of attack which is valid for uniform or weak sheared flows and high-frequency gusts.		
Piquee, J.; Canalejo, I.L.; Breitsamter, C.; Wuchner, R.; and Bletzinger, K.U	Aerodynamic Analysis of a Generic Wing featuring an Elasto-Flexible	2019	Computational and Experimental Method	Various angle of attack and Reynolds number	At small angles of attack, a positive membrane deflection and an increase in the airfoil's camber were observed	The aeroelasticity phenomenon was not considered to determine the susceptibility to flutter phenomenon	Elasto Flexible lifting surface	-

	Lifting Surface; Advances in aerodynamics							

III. CONCLUSION AND SUGGESTIONS

Following the trends and work of many researchers and a need to control noise emanating from aircraft wing, a line of progress can actually be said to have been achieved. The field is still open to more development and discovery of new techniques towards reduction of noise. Combining some of these techniques can also be of a great help towards further reduction in the level of noise emanating from aircraft wing. More different serration pattern can be made and compared with other likely addictive fixtures that can enhance the performance of serration in reducing noise emanating from aircraft wing. Feather like wing which can be actuated more accurately and designed fully along the nature of owl's wing can be a top notched but surely require a complex mechanical system to actualize. Introduction of new types of wing tips is also encouraged to reduce buildup of vortices along the wing tip which are a potential source of noise. Reduction of turbulent friction drag by the use of active high lift and actuation devices of high accuracy is needed. All these will directly contribute to noise reduction and improve aerodynamic performance of an aircraft wing.

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