Documents

Ibren, M., Andan, A.D., Asrar, W.

Numerical Prediction of Trailing Edge Noise at Low Reynolds Number with Modified Trailing Edges of a NACA 0015 Airfoil

(2024) *CFD Letters*, 16 (8), pp. 64-94.

DOI: 10.37934/cfdl.16.8.6494

Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, 53100, Malaysia

Abstract
Global concern about high noise levels in areas near airports and wind farms has generated interest from various groups due to factors such as potential health problems and dissatisfaction among the local community. To accommodate this worthwhile plan of further reducing overall noise levels, some researchers are working on lowering the contribution of trailing-edge noise. The original scientific contribution of this study lies on understanding the efficiency of various trailing edge designs such as baseline, serrations, comb and comb-serrated, across different angles of attack and Reynolds numbers, while also addressing the limitations of existing geometrical models for trailing edges. The study intends to examine the performance of these different configurations, with an emphasis on their effect on acoustic responses. By utilizing large-eddy simulation and applying the Ffowcs-Williams and Hawkings models for noise prediction, an investigation was conducted to assess the impact of these trailing edge configurations on radiated noise at a low Reynolds number of 1.6× 105. The numerical predictions of lift coefficient and surface pressure fluctuations are compared and validated with a published study and experimental data, showing satisfactory results. Further analysis of these study has demonstrated that prominent peaks at lower frequencies (<103) are observed, which are identified as the characteristic frequencies. Moreover, results showed irregular broadband noise (300-600 Hz) with increased noise and shifting peak frequency as angle of attack rose. The serrated trailing edge design notably reduced noise levels by roughly 21 dB, especially for low frequencies. Comb-serration increased high-frequency noise by about 9 dB for angles of attack at 0,-1, and-20, and achieved a reduction of approximately 9 dB for angles of attack at 1 and 20. On the other hand, the directivity pattern showed that the maximum noise level is observed to predominantly radiate at an azimuth angle of around 90 degrees for all the cases, ranging from 900 to 2700, indicating that the majority of the source's acoustic energy is being emitted on the suction and pressure sides of the airfoil.

Author Keywords
Aeroacoustics; Comb; Low-Reynolds Number; NACA0015 Airfoil; Serration; Trailing-Edge Noise

References

- Roslan, Siti Amni Husna, Rasid, Zainudin A., Ariffin, Ahmad Kamal
  Extended blade element momentum theory for the design of small-scale wind turbines
  (2023) *Journal of Advanced Research in Applied Mechanics*, 101 (1), pp. 62-75.

- Celik, Alper, Luke Bowen, J., Azarpeyvand, Mahdi
  Effect of trailing-edge bevel on the aeroacoustics of a flat-plate
  (2020) *Physics of Fluids*, 32 (10).

- Wang, Lei, Liu, Xiaomin, Li, Dian
  Noise reduction mechanism of airfoils with leading-edge serrations and surface ridges inspired by owl wings
  (2021) *Physics of Fluids*, 33 (1).

- Chong, Tze Pei, Dubois, Elisa
  Optimization of the poro-serrated trailing edges for airfoil broadband noise reduction
  (2016) *The Journal of the Acoustical Society of America*, 140 (2), pp. 1361-1373.

- Vemuri, S. H., Liu, Xiao, Zang, B., Azarpeyvand, Mahdi
  On the use of leading-edge serrations for noise control in a tandem airfoil configuration
  (2020) *Physics of Fluids*, 32 (7).

- Ramli, Muhammad Ridzwan, Mohamed, Wan Mazlina Wan, Yusoff, Hamid, Ismail, Mohd Azmi, Mansor, Ahmed Awaludeen, Hussin, Azmi, Yamin, Aliff Farhan Mohd
  The Aerodynamic Characteristics Investigation on NACA 0012 Airfoil with Owl's Wing Serrations for Future Air Vehicle
  (2023) *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 102 (1), pp. 171-183.

- Jefferies, R.
  Continuous Lower Energy, Emissions and Noise (CLEEN) Program
  (2013) *USACA Spring Association Meeting*,
  21 May

- Dobrzynski, Werner
  Almost 40 years of airframe noise research: what did we achieve?
  (2010) *Journal of aircraft*, 47 (2), pp. 353-367.

- Kallas, Siim, Geoghegan-Quinn, Máire, Darecki, M., Edelstenne, C., Enders, T., Fernandez, E., Hartman, P.
  Flightpath 2050 Europe's vision for aviation
  (2011) *Report of the high level group on aviation research*,
  European commission, Brussels, Belgium, Report No. EUR 98

- Camussi, Roberto, Bennett, Gareth J.
  Aeroacoustics research in Europe: The CEAS-ASC report on 2019 highlights
  (2020) *Journal of Sound and Vibration*, 484, p. 115540.

- Chin, Wen Jun, See, Kai Sheng, Ng, Yu Han, Gan, Jie Ling, Lim, Sing Yee
  Technologies for Indoor Noise Attenuation: A Short Review
  (2019) *Progress in Energy and Environment*, pp. 1-10.

- Gély, Denis, Bennett, Gareth J.
  Aeroacoustics research in Europe: The CEAS-ASC report on 2018 highlights
  (2019) *Journal of Sound and Vibration*, 463, p. 114950.

- (2018) *Environmental noise guidelines for the European region*,
  World Health Organization. World Health Organization. Regional Office for Europe

- Uppu, Shiva Prasad, Krishnan, Naren Shankar Radha
  Turbulent Airflows over Serrated Wings: A Review on Experimental and Numerical Analysis
  (2023) *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 109 (1), pp. 27-40.

- Ibren, Mohamed, Andan, Amelda Dianne, Asrar, Waqar, Sulaeman, Erwin
  A Review on Generation and Mitigation of Airfoil Self-Induced Noise
  (2022) *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 90 (1), pp. 163-178.

- Kroeger, Richard A., Gruschka, H. D., Helvey, Tibor C.
  Low speed aerodynamics for ultra-quiet flight
  (1972),
  Air Force Flight Dynamics Laboratory, Air Force Systems Command, United States Air Force

- Sarradj, Ennes, Fritzsche, Christoph, Geyer, Thomas
  Silent owl flight: bird flyover noise measurements
  (2011) *AIAA journal*, 49 (4), pp. 769-779.

- Graham, R. R.
  The silent flight of owls

(1934) *The Aeronautical Journal*, 38 (286), pp. 837-843.

- Herr, Michaela, Rossignol, Karl-Stephane, Delfs, Jan, Lippitz, Nicolas, Mößner, Michael
Specification of porous materials for low-noise trailing-edge applications
(2014) *20th AIAA/CEAS aeroacoustics conference*, p. 3041.

- Sandberg, R. D., Jones, L. E., Sandham, N. D., Joseph, P. F.
Direct numerical simulations of tonal noise generated by laminar flow past airfoils
(2009) *Journal of Sound and Vibration*, 320 (4-5), pp. 838-858.

- Andan, Amelda Dianne, Lee, Duck-Joo
Discrete Tonal Noise of NACA0015 Airfoil at Low Reynolds Number
(2019) *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 53 (1), pp. 129-145.

- Rossian, Lennart, Ewert, Roland, Delfs, Jan W.
Numerical investigation of porous materials for trailing edge noise reduction
(2020) *International Journal of Aeroacoustics*, 19 (6-8), pp. 347-364.

- Lee, Seongkyu, Shum, Jessica G.
Prediction of airfoil trailing-edge noise using empirical wall-pressure spectrum models
(2019) *AIAA Journal*, 57 (3), pp. 888-897.

- Oberai, Assad A., Roknaldin, Farzam, Hughes, Thomas JR
Computation of trailing-edge noise due to turbulent flow over an airfoil
(2002) *AIAA journal*, 40 (11), pp. 2206-2216.

- Wang, Meng, Moin, Parviz
Computation of trailing-edge flow and noise using large-eddy simulation
(2000) *AIAA journal*, 38 (12), pp. 2201-2209.

- Wagner, Siegfried, Bareiss, Rainer, Guidati, Gianfranco
(2012) *Wind turbine noise*,
Springer Science & Business Media

- Afshari, Abbas, Dehghan, Ali A., Azarpeyvand, Mahdi
Novel three-dimensional surface treatments for trailing-edge noise reduction
(2019) *AIAA Journal*, 57 (10), pp. 4527-4535.

- Moreau, Danielle J., Brooks, Laura A., Doolan, Con J.
The effect of boundary layer type on trailing edge noise from sharp-edged flat plates at low-to-moderate Reynolds number
(2012) *Journal of Sound and Vibration*, 331 (17), pp. 3976-3988.

- Chen, Nanshu, Liu, Hanru, Liu, Qian, Zhao, Xingyu, Wang, Yangang
Effects and mechanisms of LES and DDES method on airfoil self-noise prediction at low to moderate Reynolds numbers
(2021) *AIP Advances*, 11 (2).

- Lee, Seongkyu
The effect of airfoil shape on trailing edge noise
(2019) *Journal of Theoretical and Computational Acoustics*, 27, p. 1850020.
02

- Oerlemans, Stefan, Sijtsma, Pieter, Méndez López, B.
Location and quantification of noise sources on a wind turbine
(2007) *Journal of sound and vibration*, 299 (4-5), pp. 869-883.

- Brooks, Thomas F., Stuart Pope, D., Marcolini, Michael A.
(1989) *Airfoil self-noise and prediction*,
L-16528

- Moreau, Danielle J., Doolan, Con J.
  Noise-reduction mechanism of a flat-plate serrated trailing edge
  (2013) *AIAA journal*, 51 (10), pp. 2513-2522.
- Barone, Matthew Franklin
  (2011) *Survey of techniques for reduction of wind turbine blade trailing edge noise*,
- Hubbard, Harvey H.
  Aeroacoustics of flight vehicles: Theory and practice. volume 1. noise sources
  (1991) *NASA reference publication*, p. 1258.
- Gregory, Nigel, O'reilly, C. L.
  (1970) *Low-speed aerodynamic characteristics of NACA 0012 aerofoil section, including the effects of upper-surface roughness simulating hoar frost*,
- Oerlemans, Stefan, Schepers, Gerard
  Prediction of wind turbine noise directivity and swish
  (2009) *Third International Meeting on Wind Turbine Noise*, pp. 17-19.
- Amiet, Roy K.
  Noise due to turbulent flow past a trailing edge
  (1976) *Journal of sound and vibration*, 47 (3), pp. 387-393.
- Howe, Michael S.
  Trailing edge noise at low Mach numbers
  (1999) *Journal of Sound and Vibration*, 225 (2), pp. 211-238.
- Gruber, Mathieu, Joseph, Phillip, Azarpeyvand, Mahdi
  An experimental investigation of novel trailing edge geometries on airfoil trailing edge noise reduction
  (2011) *19th AIAA/CEAS aeroacoustics conference*, p. 2013.
- Lyu, Benshuai, Azarpeyvand, Mahdi, Sinayoko, Samuel
  Prediction of noise from serrated trailing edges
  (2016) *Journal of Fluid Mechanics*, 793, pp. 556-588.
- Stalnov, Oksana, Chaitanya, Paruchuri, Joseph, Phillip F.
  Towards a non-empirical trailing edge noise prediction model
  (2016) *Journal of Sound and Vibration*, 372, pp. 50-68.
- Chase, David M.
  Noise radiated from an edge in turbulent flow
  (1975) *AIAA journal*, 13 (8), pp. 1041-1047.
- Williams, JE Ffowcs, Hall, L. H.
  Aerodynamic sound generation by turbulent flow in the vicinity of a scattering half plane
  (1970) *Journal of fluid mechanics*, 40 (4), pp. 657-670.
- Howe, Michael S.
  A review of the theory of trailing edge noise
  (1978) *Journal of sound and vibration*, 61 (3), pp. 437-465.
- Brooks, Thomas F., Hodgson, T. H.
  Trailing edge noise prediction from measured surface pressures
  (1981) *Journal of sound and vibration*, 78 (1), pp. 69-117.
- Avallone, F., Van Der Velden, W. C. P., Ragni, D., Casalino, D.
  Noise reduction mechanisms of sawtooth and combed-sawtooth trailing-edge serrations
  (2018) *Journal of Fluid Mechanics*, 848, pp. 560-591.

- Jones, L. E., Sandberg, R. D.
  Acoustic and hydrodynamic analysis of the flow around an aerofoil with trailing-edge serrations
  (2012) *Journal of Fluid Mechanics*, 706, pp. 295-322.
- Arce León, Carlos, Merino-Martínez, Roberto, Ragni, Daniele, Avallone, Francesco, Snellen, Mirjam
  Boundary layer characterization and acoustic measurements of flow-aligned trailing edge serrations
  (2016) *Experiments in fluids*, 57, pp. 1-22.
- Avallone, Francesco, Pröbsting, Stefan, Ragni, Daniele
  Three-dimensional flow field over a trailing-edge serration and implications on broadband noise
  (2016) *Physics of Fluids*, 28 (11).
- Dassen, T., Parchen, R., Bruggeman, J., Hagg, F.
  (1996) *Results of a wind tunnel study on the reduction of airfoil self-noise by the application of serrated blade trailing edges*,
- Oerlemans, Stefan, Fisher, Murray, Maeder, Thierry, Kögler, Klaus
  Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations
  (2009) *AIAA journal*, 47 (6), pp. 1470-1481.
- Gruber, Mathieu
  (2012) *Airfoil noise reduction by edge treatments*,
  PhD diss., University of Southampton
- Chong, Tze Pei, Vathylakis, Alexandros
  On the aeroacoustic and flow structures developed on a flat plate with a serrated sawtooth trailing edge
  (2015) *Journal of Sound and Vibration*, 354, pp. 65-90.
- León, Carlos Arce, Merino-Martínez, Roberto, Ragni, Daniele, Avallone, Francesco, Scarano, Fulvio, Pröbsting, Stefan, Snellen, Mirjam, Madsen, Jesper
  Effect of trailing edge serration-flow misalignment on airfoil noise emissions
  (2017) *Journal of Sound and Vibration*, 405, pp. 19-33.
- Avallone, Francesco, Pröbsting, Stefan, Ragni, Daniele
  Three-dimensional flow field over a trailing-edge serration and implications on broadband noise
  (2016) *Physics of Fluids*, 28 (11).
- Gruber, Mathieu, Joseph, Phillip, Chong, Tze
  On the mechanisms of serrated airfoil trailing edge noise reduction
  (2011) *17th AIAA/CEAS aeroacoustics conference (32nd AIAA aeroacoustics conference)*, p. 2781.
- Jaworski, Justin W., Peake, Nigel
  Aeroacoustics of silent owl flight
  (2020) *Annual Review of Fluid Mechanics*, 52, pp. 395-420.
- Szőke, Máté, Fiscaletti, Daniele, Azarpeyvand, Mahdi
  Uniform flow injection into a turbulent boundary layer for trailing edge noise reduction
  (2020) *Physics of Fluids*, 32 (8).
- Geyer, Thomas, Sarradj, Ennes, Fritzsche, Christoph
  Measurement of the noise generation at the trailing edge of porous airfoils

(2010) *Experiments in fluids*, 48, pp. 291-308.

- Bae, Youngmin, Moon, Young J.
  Effect of passive porous surface on the trailing-edge noise
  (2011) *Physics of Fluids*, 23 (12).

- Ali, Syamir Alihan Showkat, Azarpeyvand, Mahdi, Roberto Ilário Da Silva, Carlos
  Trailing-edge flow and noise control using porous treatments
  (2018) *Journal of Fluid Mechanics*, 850, pp. 83-119.

- Finez, Arthur, Jacob, Marc, Jondeau, Emmanuel, Roger, Michel
  Broadband noise reduction with trailing edge brushes
  (2010) *16th AIAA/CEAS aeroacoustics conference*, p. 3980.

- Herr, Michaela, Dobrzynski, Werner
  Experimental Investigations in Low-Noise Trailing Edge Design
  (2005) *AIAA journal*, 43 (6), pp. 1167-1175.

- Clark, Ian A., Nathan Alexander, W., Devenport, William, Glegg, Stewart, Jaworski, Justin W., Daly, Conor, Peake, Nigel
  Bioinspired trailing-edge noise control
  (2017) *AIAA Journal*, 55 (3), pp. 740-754.

- Jawahar, Hasan Kamliya, Ai, Qing, Azarpeyvand, Mahdi
  Experimental and numerical investigation of aerodynamic performance for airfoils with morphed trailing edges
  (2018) *Renewable Energy*, 127, pp. 355-367.

- Talboys, Edward, Geyer, Thomas F., Brücker, Christoph
  An aeroacoustic investigation into the effect of self-oscillating trailing edge flaplets
  (2019) *Journal of Fluids and Structures*, 91, p. 102598.

- Chong, Tze Pei, Joseph, Phillip F.
  An experimental study of airfoil instability tonal noise with trailing edge serrations
  (2013) *Journal of Sound and Vibration*, 332 (24), pp. 6335-6358.

- León, Carlos Arce, Merino-Martínez, Roberto, Ragni, Daniele, Avallone, Francesco, Scarano, Fulvio, Pröbsting, Stefan, Snellen, Mirjam, Madsen, Jesper
  Effect of trailing edge serration-flow misalignment on airfoil noise emissions
  (2017) *Journal of Sound and Vibration*, 405, pp. 19-33.

- Chong, T. P., Joseph, P. F., Gruber, M.
  Airfoil self noise reduction by non-flat plate type trailing edge serrations
  (2013) *Applied Acoustics*, 74 (4), pp. 607-613.

- Bohn, A. J.
  Edge noise attenuation by porous-edge extensions
  (1976) *14th aerospace sciences meeting*, p. 80.

- Potter, C.
  (1968) *An experiment to examine the effect of porous trailing edges on the sound generated by blades in an airflow*,
  American Institute of Aeronautics and Astronautics

- Herr, Michaela, Reichenberger, Johann
  In search of airworthy trailing-edge noise reduction means
  (2011) *17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference)*, p. 2780.

- Sarradj, Ennes, Geyer, Thomas
  Noise generation by porous airfoils

(2007) *13th AIAA/CEAS Aeroacoustics Conference (28th AIAA Aeroacoustics Conference)*, p. 3719.

- Geyer, Thomas, Sarradj, Ennes, Fritzsche, Christoph
  Porous airfoils: noise reduction and boundary layer effects
  (2010) *International journal of aeroacoustics*, 9 (6), pp. 787-820.

- Geyer, Thomas F., Sarradj, Ennes
  Trailing edge noise of partially porous airfoils
  (2014) *20th AIAA/CEAS aeroacoustics conference*, p. 3039.

- Zhang, Minghui, Chong, Tze Pei
  Experimental investigation of the impact of porous parameters on trailing-edge noise
  (2020) *Journal of Sound and Vibration*, 489, p. 115694.

- Geyer, Thomas Fritz, Sarradj, Ennes
  Self noise reduction and aerodynamics of airfoils with porous trailing edges
  (2019) *Acoustics*, 1 (2), pp. 393-409.
  MDPI

- Revell, James, Revell, James, Kuntz, Herbert, Balena, Frank, Horne, Clifton, Storms, Bruce, Dougherty, Robert
  Trailing-edge flap noise reduction by porous acoustic treatment
  (1997) *3rd AIAA/CEAS aeroacoustics conference*, p. 1646.

- Bernicke, Paul, Akkermans, R. A. D., Ananthan, Varun B., Ewert, Roland, Dierke, Jürgen, Rossian, Lennart
  A zonal noise prediction method for trailing-edge noise with a porous model
  (2019) *International Journal of Heat and Fluid Flow*, 80, p. 108469.

- Wagner, Claus, Hüttl, Thomas, Sagaut, Pierre
  (2007) *Large-eddy simulation for acoustics*, 20.
  eds. Cambridge University Press

- Storey, R. C., Norris, S. E., Cater, J. E.
  Modelling turbine loads during an extreme coherent gust using large eddy simulation
  (2014) *Journal of Physics: Conference Series*, 524 (1), p. 012177.
  IOP Publishing

- Kim, Sung-Eun
  Large eddy simulation using an unstructured mesh based finite-volume solver
  (2004) *34th AIAA fluid dynamics conference and exhibit*, p. 2548.

- Smagorinsky, Joseph
  General circulation experiments with the primitive equations: I. The basic experiment
  (1963) *Monthly weather review*, 91 (3), pp. 99-164.

- Germano, Massimo, Piomelli, Ugo, Moin, Parviz, Cabot, William H.
  A dynamic subgrid-scale eddy viscosity model
  (1991) *Physics of Fluids A: Fluid Dynamics*, 3 (7), pp. 1760-1765.

- Zhao, Dan, Han, Nuomin, Goh, Ernest, Cater, John, Reinecke, Arne
  (2019) *Wind turbines and aerodynamics energy harvesters*,
  Academic Press

- Lighthill, Michael James
  On sound generated aerodynamically I. General theory

(1952) *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 211 (1107), pp. 564-587.

- Lighthill, Michael James
On sound generated aerodynamically II. Turbulence as a source of sound
(1954) *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 222 (1148), pp. 1-32.

- Williams, JE Ffowcs, Hawkings, David L.
Sound generation by turbulence and surfaces in arbitrary motion
(1969) *Philosophical Transactions for the Royal Society of London. Series A, Mathematical and Physical Sciences*, pp. 321-342.

- Shen, Wen Zhong, Zhu, Weijun, Sørensen, Jens Nørkær
Aeroacoustic computations for turbulent airfoil flows
(2009) *AIAA journal*, 47 (6), pp. 1518-1527.

Correspondence Address
Andan A.D.; Department of Mechanical Engineering, Malaysia; email: ameldadianne@iium.edu.my

Publisher: Semarak Ilmu Publishing

ISSN: 21801363
Language of Original Document: English
Abbreviated Source Title: CFD Lett.
2-s2.0-85191173040
Document Type: Article
Publication Stage: Final
Source: Scopus