NUMERICAL SIMULATIONS OF FLOW PAST A MULTI-ELEMENT AIRFOIL SYSTEM AND RESULTING NOISE RADIATION

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
July 2024

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by

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Submitted
in fulfillment of the requirements of the degree of Doctor of Philosophy
to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2024

Certificate

This is to certify that the thesis entitled **"Numerical simulations of flow past a multi-element airfoil system and resulting noise radiation"**, being submitted by **Deepak Kumar Singh** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a record of the bonafide research carried out by him which has been prepared under our supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. The research reports and results presented in the thesis has not been submitted for any degree or diploma in any other university or institute.

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Acknowledgements

My gratitude goes to my supervisor Prof. Arjun Sharma and my committee members, Prof. Sanjeev Sanghi, Prof. Arghya Samanta, and Prof. Subodh V. Modak. I gratefully acknowledge them for being a part of my research committee and reviewing my dissertation. This research would not have been possible without the financial assistance provided by the institute fellowship. I would like to acknowledge the Applied Mechanics Department of IIT Delhi for providing all the necessary equipment and lab space to carry out the current work. Support from a research grant (ECR/2017/001770) by the Science and Engineering Research Board, India, is also thankfully acknowledged. A special thanks to the supercomputing facility at IIT Delhi. I would like to express my gratitude to Dr. Manish Aggarwal for helping me with the supercomputing facility. I would like to thank everyone else who played an important role in completing this work and also express an apology if I have forgotten to thank someone.

DEEPAK KUMAR SINGH

Abstract

A detailed study of aerodynamics of generic multi-element airfoil configurations is presented at moderate values of Reynolds number (in the range $5\times10^4-1.5\times10^5$) and Mach numbers in the range < 0.4. Several studies are reported on aerodynamics of high-lift systems at high-Reynolds number but the areas of low and moderate Reynolds number flow regimes have gained interest recently due to their applications in the design of unmanned aerial vehicles (UAV) and micro-aerial vehicles (MAV). Parametric studies of flows past single, two- and three-element airfoils are conducted using Reynolds-Averaged-Navier-Stokes simulations with single equation Spalart-Allmaras turbulence model, to study dependencies on several geometric parameters that appear in the problem. Unsteady compressible flow effects, including the generation of noise at the trailing edge, are also studied using numerical solutions of two-dimensional Navier Stokes equations.

A two-element airfoil is systematically developed using NACA0012 and NACA23012 airfoils for the main element and flap, respectively. A detailed study of effects of flap geometric parameters (overlap, gap-width and deflection angle) on flow is conducted at Reynolds number of 5×10^4 and a configuration of maximum lift is identified. The trailing edge of the main element is subsequently modified to a cusped shape to increase the range of flap overlap and influencing the pressure distribution on flap to prevent early flow separation. With the application of active flow control in the form of steady blowing/suction, a $9-13\%$ increase in values of lift coefficients to a maximum value of approximately 1.5 is achieved when the free-stream angle of attack is 5^o. The influence of viscous effects such as a laminar separation bubble, boundary layer formation in the slot region between the flap and the main element are examined in detail. In the next step, a slat is positioned upstream of the two-element airfoil. Two angles of attack of 5^o and 13^o at Reynolds number of 1.5×10^5 are considered to analyse the effects of slat geometric camber and deflection angle for a fixed value of slat gap and overlap. Aerodynamic performance of the three-element airfoil is sensitive to the boundary layer that evolves on the slat surface. Both the geometric parameters are found to have a significant effect on the merging of the slat wake and the boundary layer on the suction surface of the main element. Implementation of suction/blowing based active flow control at the slat surface is found to yield a thinner slat wake and delay wake-boundary layer confluence to aft positions on the main element. With adjustments in slat deflection and application of active flow control, the maximum lift coefficient is found to increase to 2.5 at angle of attack of 13^o for the three-element airfoil up from a value of 1.6 for the two-element airfoil at angle of attack of 7^o.

The occurence of trailing edge noise radiation from a single and two-element airfoil is studied using numerical solutions of two-dimensional compressible Navier Stokes equations at Reynolds number of 5×10^4 and angle of attack of zero degrees. Several verfication and validation tests of the in-house computer program used for research are presented. In the case of single airfoil, vortex shedding and the scattering of pressure fluctuations at the trailing edge is found to result in tonal noise radiation. In the case of two-element airfoil, merging of the wake of the main element with the shear layer that separates off the flap results in rapid development of flow unsteadiness and mixing due to appearance of small scales, away from the trailing edges of main element and flap. The noise radiated from the two-element airfoil is consequently lower in amplitude compared to that from the single airfoil.

सार

सामान्य बहु-तत्व वायुपत्रक विन्यास के वायुगतिकी का विस्तृत अध्ययन रेनॉल्ड्स संख्या के मध्यम मानों $(5 \times 10^4 - 1.5 \times 10^5$ की सीमा में) और मैक संख्याओं की सीमा < 0.4 पर प्रस्तुत किया गया है। उच्च-रेनॉल्ड्स संख्या पर उच्च-लिफ्ट प्रणालियों के वायुगतिकी पर कई अध्ययनों की रिपोर्ट की गई है, लेकिन निम्न और मध्यम रेनॉल्ड्स संख्या प्रवाह व्यवस्थाओं के क्षेत्रों ने मानव रहित हवाई वाहनों और माइक्रो-एरियल वाहनों के डिजाइन में उनके अनुप्रयोगों के कारण हाल ही में रुचि प्राप्त की है। समस्या में दिखाई देने वाले कई ज्यामितीय मापदंडों पर निर्भरता का अध्ययन करने के लिए, एकल समीकरण स्पालार्ट-अल्मारस टर्बुलेंस मॉडल के साथ रेनॉल्ड्स-औसत-नेवियर स्टोक्स सिमुलेशन का उपयोग करके एकल, दो- और तीन-तत्व वायुपत्रक से पहले के प्रवाह के पैरामीट्रिक अध्ययन किए जाते हैं। अस्थिर संपीड़ित प्रवाह प्रभावों, जिसमें अनुगामी किनारे पर शोर की उत्पत्ति भी शामिल है, का अध्ययन द्वि-आयामी नेवियर स्टोक्स समीकरणों के संख्यात्मक समाधानों का उपयोग करके भी किया जाता है।

मुख्य तत्व और फ्लैप के लिए क्रमशः NACA0012 और NACA23012 वायुपत्रक का उपयोग करके एक दो-तत्व वायुपत्रक व्यवस्थित रूप से विकसित किया गया है। फ्लैप ज्यामितीय मापदंडों (ओवरलैप, गैप-चौड़ाई और विक्षेपण कोण) के प्रवाह पर प्रभावों का एक विस्तृत अध्ययन 5×10^4 के रेनॉल्ड्स संख्या पर किया गया है और अधिकतम लिफ्ट के विन्यास की पहचान की गई है। मुख्य तत्व के अनुगामी किनारे को बाद में फ्लैप ओवरलैप की सीमा को बढ़ाने और प्रारंभिक प्रवाह पृथक्करण को रोकने के लिए फ्लैप पर दबाव वितरण को प्रभावित करने के लिए एक घुमावदार आकार में संशोधित किया गया है। स्थिर ब्लोइंग/सक्शन के रूप में सक्रिय प्रवाह नियंत्रण के अनुप्रयोग के साथ, लिफ्ट गुणांक के मूल्यों में 9 - 13% की वृद्धि लगभग 1.5 के अधिकतम मूल्य तक प्राप्त की जाती है, जब फ्री-

स्ट्रीम एंगल ऑफ़ अटैक 5^o होता है अगले चरण में, दो-तत्व वाले वायुपत्रक के ऊपर की ओर एक स्लैट को रखा जाता है। स्लैट गैप और ओवरलैप के एक निश्चित मान के लिए स्लैट ज्यामितीय कैम्बर और विक्षेपण कोण के प्रभावों का विश्लेषण करने के लिए 1.5×10^5 के रेनॉल्ड्स संख्या पर 5^o और 13^o के दो हमले के कोणों पर विचार किया जाता है। तीन-तत्व वाले वायुपत्रक का वायुगतिकीय प्रदर्शन स्लैट सतह पर विकसित होने वाली सीमा परत के प्रति संवेदनशील होता है। दोनों ज्यामितीय मापदंडों का मुख्य तत्व की सक्शन सतह पर स्लैट वेक और सीमा परत के विलय पर महत्वपूर्ण प्रभाव पाया जाता है। स्लैट सतह पर सक्शन/ब्लोइंग आधारित सक्रिय प्रवाह नियंत्रण के कार्यान्वयन से एक पतली स्लैट वेक प्राप्त होती है और मुख्य तत्व पर पीछे की स्थिति में वेक-सीमा परत संगम में देरी होती है। स्लैट विक्षेपण में समायोजन और सक्रिय प्रवाह नियंत्रण के अनुप्रयोग के साथ, अधिकतम लिफ्ट गुणांक 13^o के हमले के कोण पर तीन-तत्व वायुपत्रक के लिए 2.5 तक बढ़ जाता है, जबकि 7^o के हमले के कोण पर दो-तत्व वायुपत्रक के लिए 1.6 के मान से।

एकल और दो-तत्व वाले वायुपत्रक से ट्रेलिंग एज शोर विकिरण की घटना का अध्ययन 5×10^4 के रेनॉल्ड्स संख्या और शून्य डिग्री के हमले के कोण पर दो-आयामी संपीड़ित नेवियर स्टोक्स समीकरणों के संख्यात्मक समाधानों का उपयोग करके किया जाता है। शोध के लिए उपयोग किए गए इन-हाउस कंप्यूटर प्रोग्राम के कई सत्यापन और सत्यापन परीक्षण प्रस्तुत किए गए हैं। एकल वायुपत्रक के मामले में, भंवर बहाव और ट्रेलिंग एज पर दबाव में उतार-चढ़ाव के बिखराव के परिणामस्वरूप टोनल शोर विकिरण होता है। दो-तत्व वाले वायुपत्रक के मामले में, मुख्य तत्व के जागने को फ्लैप से अलग करने वाली कतरनी परत के साथ विलय करने से मुख्य तत्व और फ्लैप के अनुगामी किनारों से दूर, छोटे पैमाने की उपस्थिति के कारण प्रवाह अस्थिरता और मिश्रण का तेजी से विकास होता है।

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List of Acronyms

CFD = Computational Fluid Dynamics

FDM = Finite Difference Method

FVM = Finite Volume Method

LES = Large Eddy Simulation

DES = Detached Eddy Simulation

MPI = Message Passing Interface

NS = Navier-Stokes

RANS = Reynolds-Averaged Navier-Stokes

LSB = Laminar Separation Bubble

List of Symbols and Abbreviations

Re	Reynolds Number
M	Mach Number
α	Angle of Attack
c	Chord Length of Main Airfoil
c_f	Chord Length of Flap
δ_f	Flap Deflection Angle
h_f	Flap Overlap
w_f	Flap Gap
c_s	Chord Length of Slat
δ_s	Slat Deflection Angle
h_s	Slat Overlap
w_s	Slat Gap
C_p	Pressure Coefficient
C_f	Skin-friction Coefficient
C_L	Lift Coefficient
C_D	Drag Coefficient