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4. TITLE AND SUBTITLE Analysis and Computation of Viscous Flows: 3D Flows, Separation and Transition	5. FUNDING NUMBERS F49620-95-1-0275
6. AUTHORS Professor Alric Rothmayer	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Iowa State University, Aerospace Engineering & Engineering Mechanics Ames, IA 50011	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 110 Duncan Avenue, Room B-115 Bolling Air Force Base, DC 20332-8080	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A triple-deck theory was developed for thermo-mechanical interaction of air, ice and water. A novel interaction regime was found in which the low speed lower - deck flow can interact with both the liquid - film/droplets and the ice growth through a Stephan condition. A new broad band icing instability was observed, which is believed can lead to the creation of complex short scale roughness and provide a mechanism to explain the sensitive dependence on initial conditions often observed in icing experiments.

14. SUBJECT TERMS triple-deck, deck flow, icing	15. NUMBER OF PAGES
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Analysis and Computation of Viscous Flows: 3D Flows, Separation and Transition
AFOSR Grant/Contract F49620–95–1–0275

Final Technical Report (due May 31, 1998)
1 May 1995 – 28 Feb 1998

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OBJECTIVES: Analysis and computation of unsteady viscous flows, separation and transition. Some redirection into general area of surface roughness impact on above areas, including distributed roughness, rain contamination, and icing.

STATUS OF EFFORT

Navier–Stokes simulations:

The two–dimensional unsteady Navier–Stokes equations in streamfunction vorticity form were applied to the direct numerical simulation of leading edge flow instabilities. Grid independent Rayleigh instabilities were computed and the Reynolds number scaling was extracted from the numerical simulations. A novel wall pressure recovery was observed for the nonlinear eddies. While the pressure in the core of the boundary layer was significantly altered from the Prandtl boundary layer values, the pressure at the edge of the boundary layer and at the wall was the same as the Prandtl values. This work is documented in in the following publications:

Bhaskaran, R., & Rothmayer, A.P., 1998, "Separation and Instabilities in the Viscous Flow Over Airfoil Leading Edges," *Computers & Fluids*. (to appear).

Bhaskaran, R., & Rothmayer, A.P., 1996, "Instabilities in the Viscous Flow Past Airfoil Leading Edges," AIAA Paper 96–2017, presented at the AIAA 27th Fluid Dynamics Conference.

The Navier–Stokes code has been used by BEAM Technologies to secure a Phase II SBIR. This work has also been extended into support of a graduate student by the NASA Lewis icing branch. The focus of the work with NASA will likely be to use both the 2D and 3D versions of the code to provide direct numerical simulations of leading edge flows with known icing roughness and to assess the impact of that roughness on leading edge separation and heat transfer.

Effects of surface roughness on laminar separation:

The first computations of supersonic breakaway separation free–interactions past an adiabatic wavy wall using triple–deck theory were performed. The intent was to see if small scale surface roughness embedded within the boundary layer could effect local breakaway separation characteristics governed by the triple–deck free–interaction, which could in turn impact upon larger scale laminar separations. Despite the novelty of the numerical computations, the results were negative. This work is documented in:

Rothmayer, A.P., 1998, "Supersonic breakaway separation past an adiabatic wavy wall," *AIAA Journal*, 36(4), April 1998, pp. 571–577.

Rothmayer, 1997, "The Effect of Surface Roughness on Breakaway Separation," AIAA Paper 97–0865, presented at the AIAA 35th Aerospace Sciences Meeting and Exhibit.

This investigation was continued using a full airfoil–scale interacting boundary layer method in low speed flow. This method captures both the local separation mechanisms and history effects associated with the roughness. It was found that roughness embedded within the boundary can, in fact, substantially alter the size of airfoil–scale laminar separations. The effect is seen to become worse with decreasing streamwise length and increasing height of the roughness (all roughness elements are within the boundary layer). Changes in size of the airfoil–scale laminar separation bubble of up to 40% were observed. This work is documented in:

Huebsch, W.W., & Rothmayer, A.P., 1998, "The Effects of Small–Scale Surface Roughness on Laminar Airfoil–Scale Trailing Edge Separation Bubbles," AIAA paper 98–0103, presented at the AIAA 36'th Aerospace Sciences Meeting.

Asymptotic Methods for Airfoils with Water and Ice Contamination:

A triple–deck theory was developed for the formation of surface waves on air–driven liquid films. Simple boundary layer results of Alving & Joseph were reproduced, but using a much more complete theory. A triple–deck structure was developed for the local wave instability and was found to govern the cross–over regime for waves on shallow and deep films. The theory was developed for liquid waves on full airfoils, and the location of maximum wave development was found to correlate with regions of precursory icing roughness formations. This work also has application to rain contamination of aerodynamic surfaces. This work is documented in:

Tsao, J.C., Rothmayer, A.P., & Ruban, A.I., 1997, "Stability of Air Flow Past Thin Liquid Films on Airfoils," *Computers & Fluids*, 26(5), pp. 427–452.

Tsao, J.C., Rothmayer, A.P., & Ruban, A.I., 1996, "Stability of Air Flow Past Thin Liquid Films on Airfoils," AIAA Paper 96–2155, presented at the AIAA 1st Theoretical Fluid Mechanics Conference.

A triple–deck theory was developed for the thermo–mechanical interaction of air, ice and water. A novel interaction regime was found in which the low speed lower–deck flow can interact with both the liquid–film/droplets and the ice growth through a Stephan condition. A new broad band icing instability was observed, which is believed can lead to the creation of complex short scale roughness and provide a mechanism to explain the sensitive dependence on initial conditions often observed in icing experiments. This work is documented in (the journal paper is in preparation):

Tsao, J.C., & Rothmayer, A.P., 1998, "A Mechanism for Ice Roughness Formation on an Airfoil Leading Edge Contributing to Glaze Ice Accretion" AIAA paper 98–0485, presented at the AIAA 36'th Aerospace Sciences Meeting.

Three–Dimensional Numerical Methods:

A number of grid generation and numerical methods have been considered for the extension of the various numerical simulations to three–dimensions. A novel numerical method for partial differential equations was developed, which is related to the level–set method of Sethian, though the details are quite different. Effectively, a complex two or three–dimensional geometry is extended to an equivalent geometry in one higher dimension. An equivalent PDE problem is posed in the higher dimensional computational space and the resulting finite difference solution is interpolated to the physical space. This method is a straightforward extension of our current asymptotic and Navier–Stokes numerical methods. The method has been developed initially for the heat conduction problem. The advantage of the method is that it permits routine solution of problems with extremely complex geometries. This work is documented in:

Rothmayer, A.P., 1998, "A Hyperdimensional Transposition Method Applied to Heat Conduction in Complex Media," AIAA Paper 98–2761, to be presented at the 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference.

PERSONNEL SUPPORTED

* Faculty

    Alric Rothmayer

* Post–Docs
* Graduate Students (supported sequentially, i.e. 1 student at any given time, some partial support)

    Rajesh Bhaskaran (PhD, 1996, currently at BEAM Technologies, Ithaca NY)
    Jen–Ching Tsao (PhD candidate, successfully defended dissertation April, 1998)
    Wade Huebsch (PhD candidate)

* Other (please list role), unsupported

    Anatoly Ruban – collaborator (travel paid by IITAP/UTRC)
        liquid layer flows
    Frank Smith – collaborator (travel paid by IITAP/UTRC)
        CRC chapters
        Online internal–flow asymptotics/CFD course
        unsteady boundary layer theory

PUBLICATIONS

* SUBMITTED
* Journal
* Conferences

* ACCEPTED
* Books/Book Chapters (3 chapters)

Rothmayer, A.P., & Smith, F.T., 1998, "Incompressible Triple–Deck Theory," Part III, Chapter 23, *CRC Handbook of Fluid Dynamics* (to appear).

Rothmayer, A.P., & Smith, F.T., 1998, "Free–Interactions and Breakaway Separation," Part III, Chapter 24, *CRC Handbook of Fluid Dynamics* (to appear).

Rothmayer, A.P., & Smith, F.T., 1998, "Solution Methods for Two–Dimensional, Steady Triple–Deck Problems," Part III, Chapter 25, *CRC Handbook of Fluid Dynamics* (to appear).

* Journals (3 publications)

Bhaskaran, R., & Rothmayer, A.P., 1998, "Separation and Instabilities in the Viscous Flow Over Airfoil Leading Edges," *Computers & Fluids.* (to appear).

Rothmayer, A.P., 1998, "Supersonic breakaway separation past an adiabatic wavy wall," *AIAA Journal*, 36(4), April 1998, pp. 571–577.

Tsao, J.C., Rothmayer, A.P., & Ruban, A.I., 1997, "Stability of Air Flow Past Thin Liquid Films on Airfoils," *Computers & Fluids*, 26(5), pp. 427–452.

* Conferences (7 publications)

Rothmayer, A.P., 1998, "A Hyperdimensional Transposition Method Applied to Heat Conduction in Complex Media," to be presented at the 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference.

Huebsch, W.W., & Rothmayer, A.P., 1998, "The Effects of Small–Scale Surface Roughness on Laminar Airfoil–Scale Trailing Edge Separation Bubbles," AIAA paper 98–0103, presented at the AIAA 36'th Aerospace Sciences Meeting.

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Bhaskaran, R., & Rothmayer, A.P., 1995, "Validation of a Navier–Stokes Solver for the Leading–Edge Flow Past Pitching and Oscillating Airfoils," proceedings of the *6th International Symposium of Computational Fluid Dynamics*, Lake Tahoe, Nevada.

INTERACTIONS/TRANSITIONS
* Participation/Presentations At Meetings, Conferences, Seminars, Etc.

Six conference presentations. One additional conference presentation in June. Seminar at University of Iowa, Iowa Institute for Hydraulics Research. Twice presented work at NASA Lewis (one informal, one seminar).

Sponsored session on Russian Fluid Dynamics at AIAA Fluid and Plasma Dynamics summer meeting in New Orleans, June 1996. Organized planning meeting to discuss collaboration with TsAGI and UTRC at same meeting.

Member of the organizing committee of the 1st AIAA Theoretical Fluid Dynamics Conference, New Orleans, June 1996.

1994–1997, Member of the AIAA Fluid Dynamics Technical Committee.

* Consultative And Advisory Functions To Other Laboratories And Agencies

1994–1997, Project director for United Technologies project in Computational & Applied Mathematics at the International Institute of Theoretical & Applied Physics at Iowa State University.

July, 1997 – present, Awarded NASA training grant in Navier–Stokes simulations applied to aircraft icing.

Preliminary consultation to Beam Technologies in Ithaca New York on strategies for flow control of unsteady viscous flows.

Advised NASA Lewis icing branch on simulation and modeling of airfoil leading edge icing. Participant in 1st NASA/FAA Aerodynamic Issues in Icing workshop (January, 1998: by invitation with three other universities).

* Transitions

Navier–Stokes code developed at ISU used by BEAM Technologies in Ithaca NY to develop, test and patent flow control concepts for viscous separation and secure a Phase II SBIR contract.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None

HONORS/AWARDS

None