Final Report

Sabbatical Leave (AY 2015-2016)

Accomplishments and Experiences

Submitted by:

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Aberdeen Proving Ground
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Brief summary of activities

In AY 2015-16 (fall, winter and spring quarters), Professor Farouk served as a Guest Researcher at the Army Research Laboratory (ARL) , Aberdeen Proving Ground, MD. ARL provided partial salary support (*1/3 of the academic year salary and additional funds for travel and relocation*) to Professor Farouk (see Appendix). He carried out collaborative research projects with the scientists and engineers at the Weapons and Materials Research Directorate (WMRD) and the Vehicle Technologies Directorate (VTD) at ARL. Research in the areas of modeling high velocity impact of projectiles on solid and liquid surfaces, plasma actuation of flows over supersonic projectiles and the time-evolution of flows induced by thermoacoustic waves generated by heated carbon nanotube wires were initiated – as detailed in the research proposal submitted by Professor Farouk earlier to ARL and Drexel University in April 2015. Professor Farouk carried out the research in residence at the ARL facilities where he was provided with office space and access to high-speed computational facilities. The research projects were carried out in collaboration with the scientists and engineers at the Impact Physics Branch and the Flight Sciences Branch at the Weapons and Materials Research Directorate (WMRD) and the Mechanics Division at the Vehicle Technologies Directorate (VTD) at the U.S. Army Research Laboratory (ARL).

I. Benefits derived by Drexel University

The immediate benefit to Drexel University was the publicity through the applicant's (Professor Farouk) presence as a Drexel faculty in a major federal research organization and funding agency (Army Research Laboratory/Army Research Office). Professor Farouk collaborated with scientists and engineers at the ARL Weapons and Materials Research Directorate (WMRD) and the Vehicle Technology Directorate (VTD). WMRD is a national scientific and engineering resource in weapons, protection, and materials technologies. The research efforts in this directorate span the gap between basic research that improves the understanding of scientific phenomena and technology generation that supports weapon and protection system developments and fielded system upgrades. Professor Farouk's research interests and capabilities aligned well with WMRD's research thrusts and initiatives. WMRD's lethality theme is to deliver the right lethality for the right threat at the right time, which can be accomplished by providing critical technology for affordable and scalable weapons effects across the full spectrum of operations.

WMRD's research interests on aerospace technology has centered on the application of CFD using high-speed computers to: atmospheric flight mechanics, high-temperature multi-species flows, reacting multiphase flows for solid propellant gun propulsion systems, and reacting multiphase flows for liquid/gel rocket propulsion systems. There was a natural fit here with the Professor Farouk’s research interests and capabilities.

Professor Farouk also carried out collaborative research with the scientists at VTD. The VTD is the principal U.S. Army organization responsible for the pursuit of mobility-related science and technologies leading to advanced capabilities and improved reliability for Army air and ground vehicles. VTD’s research interests in the carbon nanotube (CNT) thin film loudspeakers matched Professor Farouk’s research interests in thermoacoustic wave generation and propagation.

The applicant’s sabbatical stay at ARL (specifically at WMRD and VTD) followed by the recent presentations given by him at Drexel campus has enabled Drexel faculty (involved in computational fluid dynamics and computational solid mechanics research) to be fully aware of the research interests and needs at ARL. This in turn will help the Drexel faculty to effectively compete for research support in the relevant research areas and to develop collaborative programs with WMRD and VTD at ARL.

II. Benefits to be derived by the Applicant

The research interests and past activities of the applicant (Professor Farouk) match well with the on-going research thrusts at WMRD and VTD at ARL. The leave period gave the applicant an opportunity to develop new ideas and obtain insights to the funding opportunities in the Impact Physics and Flight Sciences areas which will enabled him to prepare proposal materials to be submitted to ARL/ARO in near future. The above research groups at WMRD is one of the best in the nation in their respective areas. The extended contact with these researchers provided the applicant a greater access to their thinking and research directions. The interactions with the engineers and scientists from a major national laboratory in dealing with ‘real world’ problems will also enable Professor Farouk to become a better informed teacher when he returns to academia in fall 2016-17.

III. Accomplishments

Research tasks in several mutually agreed upon areas were carried out by Professor Farouk in collaboration with the WMRD and VTD scientists and engineers at the Army Research Laboratory, Aberdeen, MD.

The ARL WMRD is a national scientific and engineering resource in weapons, protection, and materials technologies. The research efforts by Professor Farouk at WMRD spanned the gap between basic research that improves the understanding of scientific phenomena and technology generation that supports weapon and protection system developments and fielded system upgrades. The Directorate executes its mission of leading the Army's research and technology program to enhance the lethality and survivability of the individual soldier and advanced weapon systems. Professor Farouk specifically collaborated with two branches within the WMRD viz. the Impact Physics Branch, and the Flight Sciences Brach for collaborative research during the sabbatical leave period.

The U.S. Army Research Laboratory's Vehicle Technology Directorate (VTD) is the principal U.S. Army organization responsible for the pursuit of mobility-related science and technologies leading to advanced capabilities and improved reliability for Army air and ground vehicles. Professor Farouk also collaborated with researchers at VTD on the application of carbon nanotube (CNT) thin film as a thermoacoustic loudspeaker. A conference paper has already been presented on the research accomplished at an international thermoacaoustics conference held in the Netherlands [1].

Collaborative research projects with WMRD

The Impact Physics (IP) Branch at WMRD carries out research in the field of terminal ballistics. Professor Farouk became familiar with the general approach used by Army researchers for studying and modeling impact events prior to the commencement of the sabbatical leave period that started in October 2015. While Professor Farouk’s past research has addressed the flows in compressible fluids and ionized gases, the work initiated at the Impact Physics branch will lead to the investigation of deformation in solids due to (hypervelocity) impact from a projectile. This area of work was new to Professor Farouk and he attempted to bring in fresh perspectives to the modelling and simulation efforts being pursued by the Impact Physics branch scientists and engineers.

A key area of investigation (in collaboration with the Impact Physics Branch IPB at WMRD) was thus to investigate the physics associated with penetration mechanics and how to simulate the relevant physics. While IPB's end goal is obviously in the realm of ballistics, the research problems addressed were generic enough to avoid any security limitations.

Due to his background in computational fluid mechanics, Professor Farouk was quite successful in simulating the hypervelocity impact problems employing a hydrocode, viz. LS-DYNA [2]. The hydrocode is a computational tool for modeling the behavior of continuous media. The specific problems to be simulated by Professor Farouk with improved EOS in a hydrocode was chosen by consultation with the IP Branch scientists at ARL.

The ricochet of a solid projectile from a solid plate (target) was investigated in detail using the LS-DYNA code. A ricochet is a rebound, bounce or skip off a surface, particularly in the case of a projectile (a bullet). Many ricochets are accidental and while the force of the deflection decelerates the projectile, it can still be energetic and almost as lethal as before the deflection. The likelihood of ricochet is dependent on many factors, including projectile shape, projectile material, spin, velocity (and distance), target material and the angle of incidence. A numerical study on aluminum projectiles ricocheting off a steel plate is presented in this paper. The numerical package LS-DYNA is used to model the process of the impact of aluminum projectile on a steel plate [3]. The simulations were carried out for a given range of projectile velocity (250 m/s to 1500 m/s) with varying impact angles. From the numerical results the ricochet angle and the ricochet velocity is predicted in terms of the incident angle and the incident velocity. The impact velocity effect on the ricochet phenomenon is studied. The numerical results were compared with available analytical solutions of the ricochet problem available in the literature.

Equation of State (EOS) is the key element in computer-based and analytical studies of hypervelocity impact phenomena. The majority of these is based on the Gruneisen assumption and Mie-Gruneisen EOS. The linkage of classical thermodynamics to lattice mechanics, as pioneered by Gruneisen (1959) is a powerful tool in deciphering condensed-matter physics. The Mie-Gruneisen EOS belongs to the class of the so-called incomplete EOS. They are called incomplete because, taken separately, they do not allow computing some essential thermodynamic characteristics of the substances. While the compression behavior in solids due to impact is well represented by the Mie-Gruneisen EOS, the tensile behavior is difficult to model, and that is an area that needs further studies. In particular, for an EOS to have general applicability with the context of a numerical code, the modeling of tensile behavior (and eventual spallation) is vital. Further developments in this area will be attempted by Professor Farouk in future when he continues the research beyond the sabbatical period at ARL.

Professor Farouk identified the application of the LS-DYNA code in interpreting the experiments in progress at WMRD using the split-Hopkinson pressure bar (SHPB). The SHPB is ideal for analyzing material behavior under non-shock wave loading. This understanding of the output of the tests at WMRD and developing techniques for reliable comparison of simulations with SHPB data will be valuable for several on-going projects at WMRD. For materials other than metals comparison with an output stress vs. strain curve is not sufficient as the assumptions built into the classical analysis are generally violated. Professor Farouk is continuing this work at Drexel University in collaboration with the scientists at WMRD

Professor Farouk also initiated collaborative efforts with the Flight Sciences Branch in WMRD in simulating high speed flows on projectile surfaces. In particular, the generation of a plasma discharge on a projectile surface appears to be of interest as this seems to be a way of producing a pressure imbalance to divert a projectile from its initial trajectory. The plasma discharge can be produced by an embedded low-voltage generator capable of delivering an electric discharge between the electrodes flush with the projectile surfaces. Professor Farouk has past experience in simulating both AC and DC plasma discharges in flow reactors for discharge characterization and deposition studies. Simulation of plasma discharges near the surface of a flow projectile in high speed flow conditions can provide important information regarding the flow control and stability of the projectile. Professor Farouk is also continuing this work at Drexel University in collaboration with the scientists at WMRD

Collaborative research project with VTD

Aligned carbon nanotube (CNT) films drawn from CNT arrays have shown the potential as thermoacoustic loudspeakers. The CNTs can generate smooth-spectra sound emission over a wide frequency range (1-10(5) Hz) by means of thermoacoustics. This area of research fits in well with Professor Farouk's, recent work on thermoacoustic wave generation and propagation in compressible media. The ongoing experimental work at the Mechanics Division at VTD on CNT loudspeakers was benefit from the proposed computational fluid dynamic studies by Professor

Farouk on sound generation and emission from CNT films due to alternating current heating. The acoustical and geometrical parameters providing increases in efficiency and transduction performance for resonant systems was investigated.

IV. Summary and Future Collaborative Efforts

The sabbatical leave program provided Professor Farouk a rewarding opportunity for to continue his professional development. The leave enabled him to pursue scholarly activities that reflect potential to him and Drexel University. The leave has already resulted in scholarly works (such as papers, technical papers) and potential improvement of teaching effectiveness.

The research experience at the Army Research Laboratory during AY 2015-16 has exposed Professor Farouk to interesting and intellectually challenging research areas that has broadened his horizons. Future collaborative efforts between the ARL scientists and Professor Farouk and his students will be pursued in the coming months.

REFRENCES

1. ‘Signal Conditioning of Carbon Nanotube Thin Film Loudspeakers’, B. Farouk, Asha Hall, Wosen Wolde, Jeremy Gaston et al., Proceedings, The third International Workshop on Thermoacoustics, A7-A15, the University of Twente in Enschede, The Netherlands October, 2015

2. ‘LS-DYNA R8.0 Keyword Users’ Manual’, Livermore Software Technology Corporation, Livermore CA, March 2015

3. ‘Ricochet of High Speed Aluminum Projectiles from a Steel Plate’ B. Farouk and S. Segletes, ASME IMECE, November 2016, Phoenix, AZ (to be presented)

Appendix

Support letter from the Army Research Laboratory,
Aberdeen Proving Ground, MD

DEPARTMENT OF THE ARMY
US ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
ABERDEEN PROVING GROUND MD 21005-5066

October 28, 2014

Bakhtier Farouk
Professor of Mechanical Engineering
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Dear Baki,

We at ARL are excited over your interest in a sabbatical at the US Army Research Laboratory (ARL) at our Aberdeen Proving Ground campus. As you discovered during your visit this past summer, there are a number of research opportunities in the underlying science and engineering that we employ to equip and defend our armed forces. Within the Impact Physics Branch (IPB) here in the Weapons and Materials Research Directorate (WMRD), we seek to understand the nature of high-speed terminal ballistic interaction. The numerical methods that are commonly employed rely on accurate equations of state for condensed matter, over the full range of material states. We believe there is opportunity for a better thermodynamic understanding of the material physics in the tensile range of behavior that leads to material failure and spallation, to which your expertise could be applied. In more general terms, the IPB is interested in having a "fresh set of eyes" look over the approaches we employ in solving various problems in terminal ballistics. I believe that you can provide a fresh view that may be well suited in that regard.

I also understand from WMRD's Flight Sciences Branch (FSB) that there is an interest in better understanding the manner and ways in which a plasma discharge on the surface of an aerodynamic body can be harnessed to reliably and predictably alter the flow field about the body. Such an alteration changes the surface loading upon the projectile, which in turn will induce a deviation in the projectile trajectory.

ARL's Vehicle Technologies Directorate (VTD) has expressed an interest in funding a portion of your sabbatical to work with them on the use of carbon nanotubes as thermoacoustic loudspeakers. While WMRD has no direct interest in supporting collaborations between yourself and ARL researchers outside of WMRD, we are willing to coordinate with other directorates to allow your sabbatical to be jointly funded.

The conditions for your sabbatical as you explained are that Drexel University would supply 2/3 of your salary and benefits for the academic year 2015-2016. The remaining 1/3 plus local travel costs are to be supplied by ARL. Based on the estimates provided in your email of September 8, 2014 (and confirmed on October 27, 2014), the total funding required of ARL to support your sabbatical for the academic year 2015-2016 is $84,480.

Administratively, ARL would use the Oak Ridge Institute for Science and Education (ORISE) and Oak Ridge Associated Universities (ORAU) as the contract mechanism. Because of our budgetary cycle, we would not be able to provide financial disbursements prior to October 1, 2015.

While it is not possible at this time to guarantee the above arrangement because our funding situation for FY2016 is not yet locked in, it would be the intention of the IPB to cover 1/3 portion of your costs discussed above if the funding can be arranged. This tentative commitment does not depend on the ability of the VTD to provide co-sponsorship of your sabbatical.

Being a military research laboratory, a successful bid for sabbatical here at the ARL will require various security concerns to be addressed prior to (and during) the sabbatical. I will work on this end to minimize the chance of unexpected surprises in that regard, which could either delay or prevent the sabbatical from coming to fruition.

I wish you the best of luck in your sabbatical application through the university. I hope that we are successful in our bid to allocate the financial resources that will make an extended stay with us in the ARL possible.

Sincerely,

Steven B. Segletes
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