Project 1.16: Flexible Multibody Dynamics Approach for Tire Dynamics Simulation
PI: Sugiyama (Iowa)

Project started: mid-2013
Project ended: 2016

Resources / Funded effort:
2013  PI .5 SM, .5 GSRA (fall only)
2014  PI 1 SM, 1 GSRA, 1 temp RA 300hr, eqpt 18k
2015  PI 1 SM, 1 GSRA, 1 temp RA 266hr
2016  PI 1.5 SM, 1 GSRA

key:
PI   Principal Investigator (faculty unless otherwise indicated)
co-PI  co-Principal Investigator (faculty unless otherwise indicated)
FAC  faculty quad member
RS  research scientist
PD  post-doctoral student
GSRA  graduate student research assistant
RA/temp  temporary student assistant (part time)
SM  summer month
AY  9 months basis
CY  calendar year – 12 month basis
Eqpt  equipment (> $5,000 requires executive committee approval)

note: research supplies and travel are not listed
Motivation, Background and Objectives:
A physics-based high-fidelity computational model for tire and soil interaction is essential to demonstrate mobility capability in various operational military scenarios, and the overall vehicle performance on sand and rough dirt roads needs to be carefully evaluated at various design stages to avoid vehicles being stuck in sand and to ensure survivability of soldiers. To establish an end-to-end off-road mobility solver, the physics-based high-fidelity tire model is developed in this study using the finite element absolute nodal coordinate formulation (ANCF) to efficiently model the tire and soft soil interaction for use in multibody off-road mobility simulation. While existing detailed explicit finite element tire models have been successfully used for predicting stresses in tires as well as the normal contact pressure distribution under steady-state rolling conditions for passenger cars, they are not suited for the analysis of transient tire dynamics under severe maneuvers of off-road military vehicles, in which transient tire force characteristics and interaction with deformable terrains play a crucial role in predicting the overall vehicle performance. Furthermore, special treatments are required to integrate these finite element models into general multibody dynamics computer algorithms for vehicle dynamics simulation due to the essential difference in formulations and solution procedures used in multibody dynamics and classical finite element approaches. For successful development of the physics-based high-fidelity computational modeling and simulation capability for tire and soil interactions, the following three key issues need to be addressed: (1) development of a physics-based tire model that can be directly integrated into general multibody dynamics computer algorithm for off-road mobility simulation; (2) development of deformable soil models that can be integrated into the tire dynamics simulation framework; and (3) development of high performance computing (HPC) schemes for continuum-based tire/soil interaction simulation. To this end, this study is aimed to develop a high-fidelity physics-based tire/soil interaction simulation capability using flexible multibody dynamics techniques based on the finite element absolute nodal coordinate formulation to eliminate the Army’s reliance on empirical tire/soil models for off-road mobility simulation.
Approach:

To achieve this goal, the following issues are addressed in this study:

1. Development of a shear deformable laminated composite shell element based on the absolute nodal coordinate formulation for modeling the complex fiber reinforced rubber tire structure;
2. Development of a physics-based tire model using the laminated composite shell elements and validation against test results provided by Yokohama Rubber (Quad member);
3. Implementation and validation of the capped Drucker-Prager continuum soil model;
4. Development of a high-fidelity tire/soil interaction model for off-road mobility simulation;
5. Experimental validation of the physics-based tire/soil interaction simulation capabilities against soil bin mobility test data obtained at the test facility at Caterpillar (Quad member).

Approach for Task #1 Existing shear deformable ANCF shell elements have severe element locking problems which deteriorate the numerical convergence as well as the accuracy. Furthermore, the large number of coordinates used in existing ANCF shell elements eventually lead to a large dimensional tire model. For this reason, a locking-free shear deformable ANCF composite shell element is developed using general continuum mechanics approach to consider the fiber reinforced rubber material of tires, which is indispensable for the development of accurate tire models. It is integrated into the general multibody dynamics computer algorithm. The enhanced assumed strain (EAS) and assumed natural strain (ANS) approaches are introduced to alleviate thickness and shear lockings, thereby achieving the locking-free composite shell element. Development of the composite shell element was added to the task in 2014 (Y2) due to inaccuracy of the normal contact pressure observed in the preliminary tire model created by an equivalent single layer material model.

Approach for Task #2 Using the ANCF composite shell element developed in Task #1, a flexible tire model is developed. To this end, an automated procedure for creating the tire cross-section model is developed first. The entire tire cross-section is divided into tread, sidewall and bead sections, and each section has different number of layers, fiber angles, material properties, and mesh size. Using the cross-section model created with the measured or design data, the input data of the structural tire model is automatically generated. The tire model developed is validated against test results provided by Industry Quad Member, Yokohama Rubber, for fundamental structural tire characteristics that include the contact pressure, load-deflection curve, and natural frequencies.

Approach for Task #3 The finite-element continuum soil model is implemented in the tire dynamics simulation code with Drucker-Prager failure model to capture the elasto-plastic soil behavior. The validation of the implementation is carried out by comparison with soil models in ABAQUS. PI and his team will coordinate with Professor Shabana at UIC for the ANCF soil model as needed.

Approach for Task #4 A computational scheme for the tire/soil interaction is developed and integrated into high-performance computing (HPC) algorithms. In particular, a parallelized collision detection algorithm for deformable tire and soil interaction is developed to reduce the overall computational cost. In the contact problem, a pair of contacting nodes on the tire and soil elements changes as the tire rolls over the deformable terrain, thus non-zero entries in the Jacobian matrix of contact forces needs to be efficiently updated to exploit sparsity of Jacobian matrix in solution process of the implicit time integration. PI and his team will coordinate with Professor Negrut at University of Wisconsin-Madison on HPC.

Approach for Task #5 The last step in the development of the high-fidelity tire/soil simulation capability is the experimental validation. To this end, PI and his team coordinate closely with Industry Quad member from Caterpillar to validate the computational model using the soil bin test facility. The triaxial
soil test is carried out for parameter identification of the continuum soil model, and then static and
dynamic load tests are conducted. The results used for the model validation include the soil sinkage and
tire forces (Fx, Fy and Fz) under different wheel loads, inflection pressures, and slip angles.

**Previous Year(s) Accomplishments:**

**2013 Q1 Tasks:**
- Incorporate the finite-segment tread model into the in-plane ANCF tire model.
- Investigate the effect of the tread model on the contact pressure distribution.

**2013 Q1 Accomplished:**
- The finite-segment tread model was integrated into the in-plane ANCF tire model to investigate
  the effect of tread blocks on the normal contact pressure distribution.
- It was found that use of the tread model (two-layer model) integrated into the in-plane ANCF
  elastic ring tire model leads to a slightly different normal contact pressure distribution from that
  of the single layer model around the center of the contact patch. This difference is attributed to
  the change in the overall bending characteristics of tires, while this effect on the tire force
  turned out to be negligibly small in the in-plane tire model.

**2013 Q2 Tasks:**
- Develop the ANCF gradient deficient shell element for the three-dimensional flexible tire model.

**2013 Q2 Accomplished:**
- A new bi-linear shear deformable ANCF plate element was formulated and implemented in a
  test code based on the plane stress assumption (i.e., the generalized elastic forces are
  formulated as an area element).
- The element lockings observed in the initial performance test were successfully eliminated by
  introducing the enhanced assumed strain (EAS) approach to the in-plane strain components and
  the assumed natural strain (ANS) approach to the transverse shear and thickness strains.
- Various element performance test results indicated the desired convergence rate of the
  element developed. The rate of convergence was identical to that of the locking-free 4-node
  MITC shell element implemented in ANSYS for large deformation static problems.
- These results were presented at ARC Annual Program Review together with motivation and end
  goal of the project.

**2013 Q3 Tasks:**
- Implement the developed ANCF shear deformable shell element into PI and his team’s general-
  purpose multibody dynamics code.
- Performance evaluation of the developed ANCF shell element.

**2013 Q3 Accomplished:**
- The bi-linear shear deformable ANCF plate element was further generalized to the continuum
  mechanics based shell element such that anisotropic and incompressible hyperelasticity
  material models indispensable for the tire modeling can be considered in the shell element. To
  this end, the plane stress assumption used in the element developed in 2013-Q2 was relaxed
  and the generalized elastic forces were formulated as a volume element using the general
  continuum mechanics approach.
- It was found that the element suffers from the Poisson’s locking which was not exhibited in the
  element developed in 2013-Q2 due to the plane stress assumption made. To overcome this
  problem, EAS approach was applied to the transverse normal strain to alleviate the Poisson’s
  and thickness locking simultaneously.
The element formulated with the continuum mechanics approach was implemented in PI and his team’s general-purpose multibody dynamics code in FORTRAN.

**2013 Q4 Tasks:**
- Modeling and implementation of the sidewall stiffness.
- Fundamental performance test for the structural deformation of the ANCF tire model.

**2013 Q4 Accomplished:**
- Benchmark tests of the new continuum mechanics based shear deformable ANCF shell elements were carried out by comparing numerical results with those of existing higher order ANCF plate element and shell element in ANSYS (SHELL181) for large deformation static and dynamic problems.
- It was demonstrated that the Poisson’s locking exhibited in the continuum mechanics based ANCF shell element was successfully eliminated and the desired rate of convergence of finite element solutions was achieved for large deformation benchmark problems.
- For the development of the new shear deformable ANCF shell element, a peer-reviewed conference paper for ASME MSNDC conference was written and submitted for review – Presented in August 2014.

**2014 Q1 Tasks:**
- Investigate anisotropic material models for laminated plates that can be integrated into the bi-linear shear deformable ANCF plate/shell elements for modeling the tire structure.
- Continue to develop the ANCF structural tire model: (1) fully continuum ANCF tire model (high-fidelity model); and (2) simplified elastic-ring ANCF tire model (medium-fidelity model). The geometry and material properties of both models are identified by the tire specification and measured data provided by Industry Quad Member.

**2014 Q1 Accomplished:**
- A single layer ANCF shell tire model was developed using an anisotropic material model. It turned out that the normal contact pressure distribution was not accurately predicted with this model due to the simplification of the material model for tires. That is, inaccurate deformation modes exhibited in the tire model resulted in the inaccurate normal contact pressure distribution. After consultation with Industry Quad Member from Yokohama Rubber, PI and his team decided to develop the laminated composite ANCF shell element based on the element developed in Y1 (2013) such that the complex fiber reinforced rubber materials and the resulting deformation coupling of tires can be precisely described.
- A journal article on the development of the continuum mechanics based bi-linear shear deformable ANCF shell element was completed and submitted to the *ASME Journal of Computational and Nonlinear Dynamics* – Accepted for publication in September, 2014.
- Dr. Soon from Caterpillar joined the project as an Industry Quad Member. Experimental data for the tire/soil interaction will be provided for validating the tire/soil interaction model under development.

**2014 Q2 Tasks:**
- Develop an 8-node solid element for modeling rubber tread blocks of the ANCF tire model. Incompressible hyperelasticity models are used for modeling rubber materials, and the tread element is validated by comparing results with those of commercial FE codes.

**2014 Q2 Accomplished:**
- The continuum mechanics based ANCF shell element was further extended to the laminated composite shell element. The element developed allows for capturing the deformation coupling that characterizes the multi-layer fiber reinforced rubber material behavior of tires.
• An automated procedure for generating the tire model input data was developed. The code developed allows for importing the measured tire cross-section data points, and then the input data of the three-dimensional tire model is automatically generated. The entire tire cross-section is divided into tread, sidewall and bead sections, and the users specify the number of layers, fiber angles, material properties, and mesh size in each section. With those information, the tire model input data is automatically generated for the tire dynamics simulation.

• A parallel computing algorithm using OpenMP was developed for the tire model.

• A tire model using the laminated composite shell element was developed and the preliminary results were presented at ARC Annual Program Review in May.

2014 Q3 Tasks:
• Integrate the solid tread elements developed in 2014 Q2 into the ANCF tire model and the model is validated by comparing numerical results with measurement results.

2014 Q3 Accomplished:
• The ANCF laminated composite shell element was validated comprehensively against composite shell elements in ANSYS. It was demonstrated that the deformation coupling between laminae with different fiber angles was correctly captured in the element developed, and numerical results of various benchmark tests obtained using the ANCF laminated composite shell element were in good agreement with analytical solutions for linear problems and with numerical solutions obtained by composite shell in ANSYS for nonlinear large deformation problems.

• The tire model was further enhanced to capture the layer property of the cross section of an actual tire provided by Industry Quad Member from Yokohama Rubber. The tire model consists of six layers in the tread section (two steel-belt layers; two rubber layers; one carcass layer; and one belt cover layer); three layers in the sidewall section (two carcass layers; and one rubber layer); and four layers in the bead section (two carcass layers; one rubber layer; and one steel-belt layer).

• The normal contact pressure, the load-deflection curve, and the contact patch lengths of the tire model were successfully validated against test data provided by Industry Quad Member from Yokohama Rubber. This validation ensures that the fundamental structural characteristics of the tire are accurately described with the tire model developed.

• The continuum mechanics based shear deformable ANCF shell element was presented by GSRA, Hiroki Yamashita, at the ASME MSNDC conference in August.

• A journal article on the use of elastic middle surface approach for the shear deformable ANCF shell element was completed and submitted to Nonlinear Dynamics – Accepted for publication in January, 2015.

• An invited article on tire models for vehicle simulation was submitted to Tire Technology International magazine for publication – Published in October, 2014. Tire Technology International is one of the leading magazines in tire industry.

2014 Q4 Tasks:
• Compare the high- and medium-fidelity ANCF tire models with tread elements in terms of accuracy and computational efficiency.

• Discuss the use of fully parameterized ANCF elements for modeling tires.

• Identify potential problems and challenges for integration with ANCF soil models of UIC & TARDEC and HPC algorithms of UW-Madison & TARDEC by summarizing (a) formulations, (b) numerical solution procedures, and (c) the computer implementation that these different teams have.
2014 Q4 Accomplished:

- Since the development of the ANCF laminated composite shell element was added to the tasks in 2014 and was conducted in Q2 and Q3, the 8-node brick element for rubber tread of the tire model was formulated and implemented in the tire simulation code in Q4.
- The enhanced assumed strain approach was used to alleviate element lockings, and the implementation was validated against ANSYS element (SOLID185) for large deformation problems with incompressible Mooney-Rivlin rubber material.
- The rubber tread blocks are integrated into the tire model and contact pressure was validated against the high-fidelity LS-DYNA tire model provided by Industry Quad Member from Yokohama Rubber.
- For the development of the ANCF structural tire model using the locking-free laminated composite shell element, a peer-reviewed conference paper for ASME MSNDC conference was completed and submitted for review – Presented in August 2015.
- After consultation with TARDEC Quad member, it was decided that comparison with fully parameterized ANCF tire model was rescheduled to 2015 Q2 to prioritize the development of ANCF soil model and tire/soil simulation capabilities at this stage. Side-by-side comparison will be carried out to justify the PI and his team’s tire modeling approach in terms of accuracy and numerical efficiency.

2015 Q1 Tasks:

- Validation of the 8-node brick element with incompressible Mooney–Rivlin material model. The validation includes comparison with ANSYS solid elements.
- Integration of the rubber tread elements into the laminated composite shell based ANCF tire model. This involves the modification of the simulation program to incorporate the rubber brick elements and to enhance the computational efficiency using parallel computing algorithms.

2015 Q1 Accomplished:

- The promised tasks in 2015 Q1 were all completed by 2014 Q4, thus PI and his team started developing continuum soil model that can be integrated into the high-fidelity flexible tire model developed in this study.
- The 96-DOF tri-cubic ANCF brick element was formulated and implemented in the tire dynamics simulation code for modeling deformable soil.
- Numerical results of static and dynamic benchmark problems indicated that the 96-DOF ANCF tri-cubic brick element was unable to achieve the desired cubic rate of convergence. Hence, when the element performance is evaluated by “accuracy vs CPU time”, the 24-DOF tri-linear brick element with the enhanced assumed strain method led to better performance for both static and dynamics problems.
- To further address this issue, a new 33-DOF brick element was developed by introducing the additional curvature nodal coordinates (the second derivative of the global position vector) at the center of the brick element. With the additional degrees of freedom, it was shown that the element lockings of the 24-DOF tri-linear brick element were alleviated without resorting to the enhanced assumed strain method needed for the 24-DOF tri-linear brick element. This element can be integrated into general multibody dynamics computer algorithms with non-incremental solution procedures. This feature is important for soil model since complex plasticity failure models are needed and elimination of the enhanced assumed strain method simplifies the formulation and implementation of the continuum soil model. The benchmark test of nonlinear dynamic problems indicated that computational time of the 33-DOF brick element is approximately 4 to 5 times faster than that of the 96-DOF ANCF tri-cubic brick element to achieve the same level of accuracy.
A journal article on the physics-based flexible tire model using the laminated composite shell element for the transient braking and cornering analysis was completed and submitted to the ASME Journal of Computational and Nonlinear Dynamics – Accepted for publication in February, 2016.

2015 Q2 Tasks:
- Validation of the composite shell based ANCF tire model with the rubber tread elements on rigid ground. The validation includes comparison of the normal contact pressure distribution with experimental results provided by Industry Quad Member from Yokohama Rubber.

2015 Q2 Accomplished:
- The promised tasks in 2015 Q2 were all completed by 2014 Q4, thus PI and his team started implementing Drucker-Prager failure model in the brick elements developed in 2015 Q1 for modeling soil behavior using the two-step return mapping algorithm.
- A collision detection algorithm for deformable tire and soil models were developed and implemented in the tire dynamics simulation code.
- Using the tire model developed by the laminated composite shell element and the continuum soil model developed by the new 33-DOF brick element with the curvature coordinates, continuum based tire/soil interaction simulation was carried out. Preliminary results were presented at ARC Annual Program Review in May.
- Furthermore, to demonstrate the tire model capability under vehicle maneuvers on rigid ground, distributed parameter LuGre dynamic tire friction model was integrated into the flexible tire model. To this end, the contact patch predicted by the structural tire model is discretized into small strips across the tire width, and then each strip is further discretized into small elements to convert the partial differential equations of the LuGre tire friction model to the set of first-order ordinary differential equations. By doing so, the structural deformation of the flexible tire model and the LuGre tire frictional force model are dynamically coupled in the final form of the equations, and these equations are integrated simultaneously forward in time at every time step. This tire model is capable of capturing the history-dependent friction-induced hysteresis observed in the transient maneuvering. The numerical results obtained were validated against test data provided by Industry Quad Member from Yokohama Rubber and those reported in the literature.
- In response to the request from TARDEC Quad member, comprehensive benchmark tests with the existing fully parameterized ANCF composite shell element were carried out to justify the tire model developed in this study. To this end, a tire model using the fully parameterized ANCF composite shell element was developed and implemented in the tire dynamic simulation code, and numerical results were compared with those of the experimentally validated PI and his team’s tire model developed in this study. Results compared included the normal contact pressure of the tire, natural frequencies of a composite plate, deflection of the cantilevered initially curved composite shell undergoing large deformation subjected to a point load. It was shown that the existing fully parameterize shell element has severe element lockings, resulting in solutions which do not agree with the reference solutions, test results of the tire contact pressure, and the load-deflection curve of the tire model. Furthermore, use of the fully parameterized shell element led to computationally intensive tire model due to larger degrees of freedom (48 DOF) and large number of Gaussian integration points per element due to the higher order polynomials used. That is, it was concluded that use of the fully parameterized shell element is not recommend due to the inaccuracy and computational inefficiency, and use of the PI and his team’s tire modeling approach based on the locking-free lower order shell element was clearly justified. It is important to notice here that both shell elements and tire models were
implemented in the same code, and the exactly same tire modeling procedure suggested by Industry Quad member from Yokohama Rubber was used to ensure fair comparison.

2015 Q3 Tasks:
- Formulation and implementation of ANCF Drucker-Prager continuum soil model.
- Identification of element lockings of ANCF solid element that include volumetric locking for incompressible soil models, and development of numerical procedures for alleviating the element lockings.

2015 Q3 Accomplished:
- Tire vibration tests were carried out using the FFT analyzer purchased with the ARC funding for validating the modal properties of tires. Using the frequency response functions and experimental modal analysis techniques, the in-plane and out-of-plane tire vibration modes were identified and compared with the simulation results. Good agreements were obtained in frequencies and mode shapes obtained by the experiment and tire model.
- In response to a concern regarding the use of low order polynomials for modeling tires, the 4-node bi-linear composite shell element was further extended to 8-node (Q8) and 9-node (Q9) bi-quadratic shell elements using the transverse gradient coordinates to demonstrate the effect of the order of polynomials on the tire model accuracy and computational efficiency. The Q8 and Q9 bi-quadratic ANCF composite shell elements were formulated and implemented using the assumed natural strain and enhanced assumed strain approaches to eliminate the element lockings. It was demonstrated with several benchmark test problems that the ideal quadratic rate of convergence was achieved with the Q8 and Q9 shell elements developed in this study.
- Using the Q8 and Q9 bi-quadratic shell elements, the flexible tire model was constructed in the same way as the bi-linear Q4 shell element tire model and the fundamental structural characteristics including the normal contact pressures, load-deflection curve and contact patch lengths were validated against the test results. Better convergence of finite element solutions was obtained than that of the bi-linear Q4 shell element. LuGre tangential tire friction model were also implemented for the Q8 and Q9 tire models. However, it turned out that Q8 and Q9 tire models are computationally more intensive to achieve the same level of accuracy due to a large number of Gaussian integration points required to obtain the generalized elastic forces for fiber reinforced rubber materials. This comparison justified the use of the bi-linear shell element originally proposed for the tire model in this study.
- The flexible tire model using the ANCF laminated composite shell element was presented by GSRA, Hiroki Yamashita, at the ASME MSNDC conference in August.

2015 Q4 Tasks:
- Validation of the ANCF Drucker-Prager continuum soil model. The validation includes comparison with ANSYS solid elements.
- Development of high-performance computing algorithms for the tire/soil simulation.

2015 Q4 Accomplished:
- Comparison with a brick element using Drucker-Prager failure model in ABAQUS indicated that large plastic strains are not correctly captured using the Lagrangian plasticity model implemented in the 33-DOF brick element with the curvature coordinates. Thus, multiplicative finite strain plasticity theory was implemented with the spatial logarithmic strain measure. Numerical results obtained using the newly implemented continuum Drucker-Prager soil model based on the multiplicative plasticity theory agreed well with those of ABAQUS soil elements.
- To improve the computational efficiency, the contact model of the tire model was improved such that contact with road surface can occur not only at the nodal points of the shell element, but also points defined within the shell element surface to ensure sufficient number of contact
points required for high-resolution normal contact pressure distribution. With this modification, the number of shell elements in the tire model was reduced by 33 % (from 2880 to 1920 elements). Furthermore, numerical Jacobian calculation for contact forces was improved such that perturbation for the finite difference is taken for nodes in contact only. These two improvements resulted in the reduction of computational time by 48 % as compared to the original code. It takes approximately 30 minutes per one tire revolution using a single CPU. The distributed parameter LuGre tire friction model is utilized for predicting shear contact stress distribution over the contact patch.

- For the development of deformable tire/soil interaction simulation capability, a peer-reviewed conference paper for ASME MSNDC conference was completed and submitted for review – Presented in August 2016.

2016 Q1 Tasks:
- Measurement of structural characteristics of an off-road tire including the load-deflection curve and normal contact pressure for the tire model validation.
- Off-road tire/soil tests using the soil bin facility at Caterpillar that include (a) triaxial soil test, (b) static load test, and (c) tire/soil interaction test.
- Data processing of test results of off-road tire/soil tests.

2016 Q1 Accomplished:
- Tire tests of an off-road tire (235/75R15) used in mobility soil bin tests at Caterpillar (Industry Quad member) were conducted at Yokohama Rubber (Industry Quad member). The normal contact pressures, contact patch lengths, and load-deflection curves were measured for various wheel loads and air pressures.
- Using the tire data provided by Yokohama Rubber, an off-road tire model was developed and validated successfully against the test data for the load-deflection curve and contact patch lengths for various tire loads and air pressures.
- Test plan for the tire/soil interaction using the mobility soil bin test facility at Caterpillar was developed and discussed with TARDEC and Industry Quad members.

2016 Q2 Tasks:
- Parameter identification of the off-road tire and the model validation.
- Parameter identification of the continuum soil model and validation.

2016 Q2 Accomplished:
- Since the off-road tire model development and validation were completed in Q1, PI and his team continued to work on the continuum soil model validation. The “capped” Drucker-Prager failure model was implemented to account for the soil consolidation effect accurately. A plate sinkage test of soil used in the literature as a benchmark problem was carried out and the simulation results were compared with those of the ABAQUS soil model for both associative and non-associative flow rules. The result agreed very well and the accuracy of the 33-DOF continuum soil model using the multiplicative finite strain plasticity theory with the capped Drucker-Prager failure model was justified.
- Using the continuum soil model developed in this study, tire/soil interaction simulation was carried out considering a tread pattern of the off-road tire developed in 2016 Q1. To capture a detailed tread pattern on the soil footprint, very fine mesh was required and high computational power was needed. For this reason, the code was parallelized using OpenMP for flexible tire and soil calculations.
- To enable the use of high-fidelity physics-based tire/soil interaction model in off-road mobility simulations, a moving soil patch algorithm was developed for the continuum-based tire/soil interaction simulation capability such that soil elements behind the rolling tire are automatically
removed and then new elements are added sequentially ahead of the tire in the traveling direction. In other words, soil behavior only in the vicinity of a rolling tire is solved by updating “active” soil region. It was shown that this procedure allows for saving a lot of memory usage and reducing the model dimensionality and computational time. It was demonstrated that use of the moving soil patch method leads to the computational time that is proportional to the traveled distance since the dimensionality of the soil model remains constant regardless of the distance considered in simulation scenarios.

- Triaxial soil tests were completed and the test data is used to identify the soil model parameters including the cohesion, friction angle, Young’s modulus, etc.
- PI and GSRA visited Caterpillar Technical Center to discuss test conditions of the soil bin mobility test. Some preliminary tests were carried out and then test parameters were determined and confirmed. The test parameters include the tire traveling speed, tire air pressure, normal load, and slip angle.

2016 Q3 Tasks:
- Validation of the continuum-based tire/soil interaction simulation model for the static and dynamic load scenarios.

2016 Q3 Accomplished:
- The parameter identification of the continuum-based soil model was carried out. The cohesion and friction angle are identified using the soil strength measured at three different confining pressures. The characteristic curve of the plastic volumetric strain and the mean effective stress was identified using the one-dimensional consolidation soil test data for the capped Drucker-Prager model.
- Using the soil parameters identified, the triaxial soil test simulation was carried out. The stress-strain curve agreed well with the test data and it was demonstrated that the soil failure phenomenon including the hardening behavior was well captured using the soil model developed in this study.
- The soil bin test was completed at Caterpillar and the test data was delivered to PI for the validation work in Q4. The test was operated at two different wheel loads (6 and 8 kN) and three different inflation pressures (180, 230, and 280 kPa). The steering angle to the direction of travel (i.e., slip angle) was set to zero and three degrees. The 3-axis tire forces (Fx, Fy, and Fz) were measured by force transducers embedded in the tire rim. The soil sinkage was measured at the middle of the groove by a depth sensor by hand. The test was run twice for each test scenario.
- The deformable tire/soil interaction simulation capabilities developed in this study was presented by GSRA, Hiroki Yamashita, at the ASME MSNDC conference in August.

2016 Q4 Tasks:
- Continue the validation of the continuum based tire/soil interaction simulation model for the dynamic load scenarios.
- Transfer the tire dynamics software for off-road mobility simulation to TARDEC.

2016 Q4 Accomplished:
- A computational tire-soil interaction model for the soil bin mobility test was developed and soil parameters in this test condition were identified. While the same type of soil was used as the triaxial compression test, the void ratio and density were vastly different from those of the triaxial test since the soil was not compacted by a roller after loosening the soil by a tiller to produce noticeable soil sinkages in each test scenario. The soil hardening parameters were also re-identified according to the soil bin test data.
- The simulation results showed good agreement with the test results in magnitude and trend, considering the variability of soil data. The following noticeable trends were observed:
Soil sinkage results: Increase in the wheel load and the tire inflation pressure leads to an increase in the soil sinkage in both simulation and test results.

Tire force results: Increase in the wheel load and inflation pressure leads to an increase in the magnitude of the longitudinal tire forces in both simulation and test results. This is attributed to the larger sinkage caused by higher inflation pressure and larger wheel load, resulting in the tire being subjected to larger resistance forces from soil to maintain a constant speed. The similar trend was observed for the lateral forces.

- It is evident from this validation effort that the fundamental tire, soil, and their interaction behavior are well predicted using the physics-based tire-soil interaction simulation capability developed in this project.
- A journal paper of the tire-soil interaction simulation capability and experimental validation results was prepared and submitted to the ASME Journal of Computational and Nonlinear Dynamics.

External Review Board Recommendations and Researcher Feedback

1. ERB Recommendations in 2013

There were no individual project reviews in 2013

2. ERB Recommendations in 2014

Comment 2014-1: What is the plan for validating the ANCF tire model?

Response: The structural ANCF tire model is validated against test date and LS-DYNA tire model provided by Industry Quad Member from Yokohama Rubber for the following structural tire characteristics: the contact pressure, contact patch lengths, and load-deflection curve. This validation was completed for the composite shell based ANCF tire model in Q3 of 2014. The tire/soil interaction model will be validated against test data obtained by soil bin test facility of Industry Quad Member from Caterpillar.

3. ERB Recommendations in 2015

Comment 2015-1(1): More clearly define what part of the test data is being used to tune the model, and what part for validation.

Response: To clearly define what part of the test data was and will be used in the parameter identification and the model validation, more details are provided below.

Parameter identification

- **Tire material properties:** Young’s modulus, shear modulus of rigidity, and Poisson’s ratio of each layer of the fiber reinforced rubber material used in the tire model are provided by Industry Quad member (Yokohama Rubber). These values are used as they are and not tuned in the validation process.

- **Tire cross section geometry:** Using the tire cut section provided by Industry Quad member (Yokohama Rubber), the cross section geometry is digitized and the tire carcass line is selected as the elastic line of the finite-element tire model using the shell element. The layer thickness and cord angle are provided by Industry Quad member.

- **Tangential tire friction parameters:** The LuGre tire friction model parameters are experimentally identified using µ-slip curve measured in the steady-state condition. The test was carried using flat belt tire test machine of Industry Quad member (Yokohama Rubber). Using the µ-slip curve, the tire friction parameters and braking/cornering stiffness are identified separately using nonlinear least squares fitting and then all the LuGre tire friction
parameters in the entire slip range are identified so that $\mu$ peak matches the test result. More details on the systematic parameter identification procedure developed by PI and GSRA for LuGre tire friction model used in this study are found in the following literature: 


**Tire Model Validation**

- **Structural properties of the tire model**: To validate the fundamental structural characteristics of the tire model, the normal contact pressure distribution, contact patch lengths for various vertical loads, and load-deflection curve are compared with test results provided by Industry Quad member. Prediction of the accurate normal contact pressure is of crucial importance in accurate prediction of tangential tire forces including the drawbar pull and the tire sinkage in off-road mobility simulation. Furthermore, the in-plane and out-of-plane natural frequencies and mode shapes of the tire model are validated against test data. The tire vibration test and experimental modal analysis were carried out on our own.

- **Tire/soil interaction model**: To validate continuum-based tire/soil simulation capability developed in this study, off-road tire test on deformable terrain using soil bin test facility of Industry Quad member (Caterpillar) will be carried out in 2016 (Y4). In this test, the soil sinkage and tire forces on deformable terrain are measured for various wheel loads and speeds, and then the test results are compared with the simulation results. The continuum soil parameters will be identified using the triaxial soil test being conducted together with the off-road tire test.

**Comment 2015-1(2)**: This is a very sophisticated physics-based model. The project benefit enormously from more test data to refine and develop the modeling approach. It would be important to identify collaborations with other projects or test faculties that can support this fundamental work.

**Response**: PI agrees with the reviewer’s comment. The tire and soil research requires large-scale test facility for the parameter identification of the tire and soil models, and the validation involving use of a flat belt tire test machine for measuring the $\mu$-slip curve and a soil bin test facility for off-road tire test. In this regard, collaboration with the other projects and Industry Quad Members is crucial. PI and his team have been effectively working with Industry Quad Members and benefited from the collaboration. PI is also willing to collaborate with other projects relevant to terramechanics and off-road mobility.

In the model validation, PI has recognized a difficulty in treating uncertainties associated with the model parameters of both tire and soil. Tire has a complex structure and various model parameters need to be identified to develop a physics-based tire model. In some cases, only limited number of test results under limited test conditions are available, making the validation process of off-road tire simulation difficult. This issue is relevant to the previous comment raised by the reviewer (Comment 2015-1(1)) regarding how the test data is used for parameter identification and validation. PI believes that this is an essential and challenging topic for tire and soil interaction simulation, and this issue has not been thoroughly addressed in the field of study. A collaboration with the project led by Professor KK Choi, focusing on “Simulation Model Validation Framework for RBDO” could allow us to propose a unique and systematic parameter identification and validation procedures for the physics-based tire/soil simulation model crucial to TARDEC.
Comment 2015-2(1): I’m concerned that the proposed approach may be too computationally intensive and difficult to calibrate to be ultimately useful for its ultimate goal to be incorporated into the NATO Reference Mobility Model. At this stage, very little model verification has been performed.

Response: In this project, the physics-based model is pursued, which is conceptually different from existing empirical tire/soil simulation models currently in use. Use of existing empirical or simplified tire models leads to faster computation, while the lack of the model generality necessitates more extensive parameter identifications, and the model parameters, in most cases, depend solely on the test conditions. Use of the high-fidelity physics-based tire model, on the other hand, ensures the model generality which is essential to demonstrate mobility capability under various terrain conditions, but leads to an increase in the model complexity and dimensionality as pointed out by the reviewer. PI recognizes that improving the computational efficiency needs to be thoroughly addressed and substantial efforts have been made so far to optimize the simulation code. Furthermore, PI and his team have been working closely with Professor Negrut and his team from University of Wisconsin-Madison to utilize the high-performance computing (HPC) techniques to speed up computation of the physics-based flexible tire/soil simulation model. This task is currently underway, and PI and his team continue their effort on HPC for the tire/soil simulation capability.

Comment 2015-2(2): More collaborative interaction and sharing of data among projects in similar areas would be very beneficial. A focus on developing benchmark case studies, including models, control computation and communication infrastructures, which can be used by several researchers, could be very useful.

Response: PI agrees with the reviewer’s comment on establishing benchmark test problems that can be shared by researchers in the community. Since sharing model and test data provided by Industry Quad members would be difficult due to non-disclosure agreements, generic benchmark problems would be developed at the academic society level, and the model data and results would be published in public. In vehicle dynamics community, various benchmark test problems were established and have been utilized for the model validation under the International Association for Vehicle System Dynamics (IAVSD). The similar effort would be pursued in the terramechanics community.

4. ERB Recommendations in 2016

Comment 2016-1: Tire dynamics are critical to the design of many military vehicles so tire modeling is very relevant to the Army and the ARC. This area has a long history but the proposed approach to integrate a physics-based tire model into a multibody dynamics code is novel. Also, improving the computational speed for off road operation with hard cornering is very challenging. Mispelled "contact pressure destitution" in slides. Very nice results for transient braking. Very impressive simulation results.

(1) How many elements for the tire?
   Response: In both on- and off-road simulations presented in the ARC program review, 1,920 laminated composite shell elements (80 elements in circumference and 24 element across the tire cross section) are used to model the tire structure.

(2) Geometric and/or material nonlinearity in the tire itself (not including friction)?
   Response: Both geometric and material nonlinearities are considered in the laminated composite shell element developed in this study. These nonlinearities play a crucial role in predicting the highly nonlinear tire structural characteristics.

(3) How is the tire model incorporated into a multibody dynamics code?
   Response: The tire model developed in this study was integrated into PI’s general-purpose multibody dynamics code using the non-incremental solution procedure adopted in most
commercial multibody dynamics codes. In addition, the tire/soil simulation capability developed in this study was successfully integrated in the HPC multi-physics off-road simulation solver called *Chrono* for TARDEC without co-simulation techniques for off-road mobility simulation.

(4) **Are soil dynamics included?**

**Response:** Yes, the soil dynamics is included. The fully nonlinear equations of motion of the capped Drucker-Prager plastic soil model are solved together with the equations of motion of the deformable tire model using a monolithic time integration solver (implicit HHT time integrator).

**Comment 2016-2:** This is basic research. The long-term value to ARC will depend on how the project evolves and what results that can be provided, and how useful they are in assessing vehicle performance. Some in the audience with a perspective on military vehicles suggested a change in direction. Even with these uncertainties, this project seems to be easily justified from a basic research point of view.

**Response:** There was a question in the ARC annual review whether or not the tire modeling approach developed in this study can be applied to the modeling of rubber band tracks. The answer is yes - it is possible. The underlying theory and computational algorithms developed for the physics-based tire model in this study are general and can be directly applied to various applications including rubber band tracks.

**Major Milestones and Deliverables since Project Start:**

<table>
<thead>
<tr>
<th>Year/Month</th>
<th>Description</th>
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<tr>
<td>2013/May</td>
<td>A new locking-free bi-linear shear deformable ANCF plate element was developed by introducing the enhanced assumed strain (EAS) and the assumed natural strain (ANS) approaches. The element performance test results indicated the desired element convergence rate and accuracy that are consistent with the order of polynomials used.</td>
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<td>2013/September</td>
<td>The bi-linear shear deformable ANCF plate element was further generalized to a continuum mechanics based shell element such that anisotropic and incompressible material models required for the tire modeling can be considered in the element. The Poisson’s locking that appears in this type of element was eliminated by applying EAS approach. It was demonstrated that the desired rate of convergence for finite element solutions was achieved for large deformation benchmark problems in both nonlinear static and dynamic problems.</td>
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<td>2014/May</td>
<td>An automated procedure for creating the ANCF tire model input data was developed. The code developed allows for importing the measured tire cross-section data points, and then the input data of the three-dimensional ANCF tire model is automatically generated. The tire cross-section was divided into tread, sidewall and bead sections, and each section can have different numbers of layers, cord angles, material properties, and mesh size.</td>
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<tr>
<td>2014/August</td>
<td>The continuum mechanics based shear deformable ANCF shell element was generalized to the laminated composite shell element to capture the complex deformation coupling of fiber reinforced rubber material of tires. Numerical results for various benchmark tests were in good agreement with analytical solutions for linear problems and with numerical results obtained by laminated solid shell elements in ANSYS for large deformation problems.</td>
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<tr>
<td>Date</td>
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<tr>
<td>2014/October</td>
<td>The flexible tire model was developed by considering the detailed tire section geometry and layer properties. The structural tire model was successfully validated against test data and LS-DYNA tire model provided by Industry Quad member from Yokohama Rubber. The contact pressure, contact patch lengths, and load-deflection curves were in good agreement with those of test data and LS-DYNA tire model.</td>
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<td>2015/February</td>
<td>A new 33-DOF brick element was developed by introducing additional curvature nodal coordinates at the center of the brick element. With the additional degrees of freedom, it was shown that the element lockings of the 24-DOF tri-linear brick element were alleviated without resorting to the enhanced assumed strain method, allowing for more straightforward implementation of Drucker-Prager failure model for the continuum soil. The benchmark test of nonlinear dynamics problems indicated that computational time of the 33-DOF brick element is approximately 4 to 5 times faster than that of the 96-DOF ANCF tri-cubic brick element to achieve the same level of accuracy.</td>
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<tr>
<td>2015/April</td>
<td>The Drucker-Prager failure model for soil was implemented using the two-step return mapping algorithm, and the tire/soil interaction simulation were carried out using the tire model developed by the laminated composite shell element and the continuum soil model developed by the 33-DOF brick element with curvature coordinates.</td>
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<td>2015/May</td>
<td>A distributed parameter LuGre dynamic tire friction model was integrated into the flexible tire model to account for shear contact stresses in the contact patch. By doing so, the structural deformation of the flexible tire model and the LuGre tire friction force model are dynamically coupled in the final form of the equations, allowing for capturing the history-dependent friction-induced hysteresis observed in transient maneuvering scenarios. The numerical results obtained were validated against test data provided by Industry Quad Member from Yokohama Rubber and those reported in the literature.</td>
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<td>2015/June</td>
<td>In response to the request from TARDEC Quad member, comprehensive benchmark tests with the existing fully parameterized ANCF composite shell element were carried out to justify the tire model developed in this study. It was shown that the existing fully parameterize shell element has severe element lockings, resulting in solutions which do not agree with the reference solutions and test results of the tire contact pressure as well as the load-deflection curve of the tire model. Furthermore, use of the fully parameterized shell element led to computationally intensive tire model due to larger degrees of freedom (48 DOF) and large number of Gaussian integration points. That is, it was concluded that use of the fully parameterized shell element is not recommend due to the inaccuracy and computational inefficiency, and use of the PI and his team’s tire modeling approach based on the locking-free lower order shell element was clearly justified.</td>
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<td>Date</td>
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<tr>
<td>2015/July</td>
<td>The tire vibration test using FFT analyzer was carried out for validating the natural frequencies and mode shapes of the flexible tire model. Using the frequency response functions and experimental modal analysis techniques, the in-plane and out-of-plane tire vibration modes were identified and compared with the simulation results. Good agreements were obtained in frequencies and mode shapes obtained by the testing and simulation.</td>
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<td>2015/August</td>
<td>The bi-quadratic shell elements using the transverse gradient coordinates were developed to demonstrate the effect of the order of polynomials on the tire model accuracy and computational efficiency. Using the Q8 and Q9 bi-quadratic shell element, the flexible tire model was constructed and the fundamental structural property including the normal contact pressures, load-deflection curve and contact patch lengths were validated. Better convergence of finite element solutions was obtained than that of the bi-linear Q4 shell element. However, Q8 and Q9 tire models are computationally more intensive to achieve the same level of accuracy and use of the bi-linear shell element originally proposed for the tire model in this study was justified.</td>
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<td>2015/December</td>
<td>A multiplicative finite strain plasticity theory was successfully implemented in 33-DOF brick element using the spatial logarithmic strain measure. Numerical results obtained using the newly implemented continuum Drucker-Prager soil model based on the multiplicative plasticity theory agreed well with those of ABAQUS soil elements.</td>
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<td>2015/December</td>
<td>To improve computational efficiency, the contact model of the shell element tire model was improved such that contact with road surface can occur not only at the nodal points of the shell element, but also points defined inside the shell element surface to obtain high-resolution normal contact pressure distribution. Furthermore, numerical Jacobian calculation for contact forces was also improved such that perturbation for the finite difference is taken for nodes in contact only. These two improvements resulted in the reduction of computational time by 48% as compared to the original code.</td>
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<td>2016/March</td>
<td>Tire tests of an off-road tire (235/75R15) used in mobility soil bin tests at Caterpillar (Industry Quad member) were conducted at Yokohama Rubber (Industry Quad member). Using the tire data provided by Yokohama Rubber, the off-road tire model was developed and validated against test data for the normal contact pressures, contact patch lengths, and load-deflection curves for various wheel loads and air pressures.</td>
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<td>2016/April</td>
<td>To enable the use of high-fidelity physics-based tire/soil interaction model in off-road mobility simulation, a new algorithm was developed such that soil behavior only in the vicinity of rolling tire is solved by updating “active” soil region, i.e., soil elements behind the rolling tire are automatically removed and then new elements are added sequentially ahead of the tire in the direction that the tire travels. It was shown that this procedure allows for saving a lot of memory usage and reducing the model dimensionality and computational time.</td>
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</table>
### 2016/June

The parameter identification of the continuum-based soil model was carried out. The cohesion and friction angle are identified using the soil strength measured at three different confining pressures, while the soil hardening parameters were identified by the one-dimensional consolidation test data for the capped Drucker-Prager continuum soil model. Using the soil parameters identified, the trial-axial soil test simulation was carried out. The stress-strain curve agreed well with the test data, demonstrating that the soil failure phenomenon including the soil hardening behavior was well captured using the soil model developed in this study.

### 2016/October

The soil bin test was completed at Caterpillar and the test data was delivered to PI for the model validation in Q4. The test was operated at two different wheel loads (6 and 8 kN) and three different inflation pressures (180, 230, and 280 kPa). The steering angle to the direction of travel (i.e., slip angle) was set to zero and three degrees. The 3-axis tire forces (Fx, Fy, and Fz) were measured by force transducers embedded in the tire rim. The soil sinkage was measured at the middle of the groove by a depth sensor by hand. The test was run twice for each test scenario.

### 2016/December

A computational tire-soil interaction model for the soil bin mobility test was developed and soil parameters were identified including the hardening parameters according to the soil bin test data. It was observed that increase in the wheel load and the tire inflation pressure leads to an increase in the soil sinkage in both simulation and test results. Furthermore, it was observed that increase in the wheel load and tire inflation pressure leads to an increase in the magnitude of the longitudinal tire forces in both simulation and test results. This is attributed to the larger sinkage caused by higher inflation pressure and larger wheel load, resulting in the tire experiencing larger resistance forces from soil to maintain a constant speed. The similar trend was observed for the lateral forces. These simulation results agree well with the test results in magnitude and trend, considering the variability of soil data.

### ARC/TARDEC/Industry Benefits:

A physics-based high-fidelity computational model for tire and soil interactions is essential to demonstrate mobility capability in various operational military scenarios, and the overall vehicle performance on sand and rough dirt roads needs to be carefully evaluated at various design stages to avoid vehicles being stuck in sand and to ensure the survivability of soldiers. To this end, substantial efforts have been made in developing computational models for deformable terrains by TARDEC and Professor Shabana at UIC; and a scalable physics-based high performance computing (HPC) modeling and simulation capability for ground vehicle mobility by TARDEC and Professor Negrut at UW-Madison. The development of the physics-based high-fidelity ANCF tire model conducted by PI and his team in Iowa contributes to the new physics-based tire simulation capability that can be integrated into the aforementioned simulation frameworks developed under TARDEC initiatives for off-road vehicle mobility. The project goal is aligned with TARDEC 30-Year Strategy (VS3–LoE1–KO2 (3.1.2); and VS1–LoE3–KO3 (1.3.3)) that addresses the computational modeling and simulation capability for mobility capability demonstration in various operational military scenarios. Coordination with different TARDEC projects facilitates the development of high-fidelity computational models. The computational models for both tires and deformable terrains are developed based on the concept of the absolute nodal coordinate formulation, thus the two models can be integrated into a single computational scheme and
the resulting equations of motion can be solved with high performance computing scheme developed for ANCFs. PI and his team closely coordinates with UIC and UW-Madison for this purpose. TARDEC benefits from this synergy. The research progress under this project was presented in Annual Program Review in 2013, 2014, 2015, and 2016.

Industry Quad Member also benefits from this ARC research project in terms of the tire design evaluation. While focus of this study is placed on off-road vehicle mobility simulation, the tire model developed in this study has a potential of predicting the transient tire forces for passenger vehicles, which requires accurate modeling of the coupling between the structural tire deformation and tire forces in transient slip ranges.

Leveraged Funding:

1. **Army Rapid Innovation Fund, Army Research Office, “Physics-Based High Performance Computing Capability for Ground Vehicle Mobility Analysis”,** (subcontract with University of Wisconsin-Madison). (PI: 100%), $246K, September 2014 – September 2016. This research focuses on developing a massively parallel software infrastructure based on open source software Chrono that supports the modeling/simulation/visualization of ground vehicle mobility analysis using physics-based deformable terrain. This leveraged funding facilitates integration of the Iowa’s physics-based high-fidelity tire model developed under ARC project into the massively parallel high-performance computing off-road mobility simulation software that Professor Negrut and his team at the University of Wisconsin-Madison have been developing with US Army TARDEC. This leverage funding allows PI and his team to further extend their tire model capability to be integrated with discrete soil models to predict the tire behavior under high slippages that cannot be accurately predicted by the finite element based continuum soil model.

2. **Yokohama Rubber, Co. Ltd. (PI: 100%), $70K, April 2013 – March 2015.** This research is aimed to develop a modeling procedure for transient tire forces under hard braking and cornering maneuvers using LuGre dynamic tire friction model for commercial passenger vehicles. This leveraged funding allows PI and his team to coordinate closely with the tire manufacturer for validating the tire model being developed in the ARC project. Yokohama Rubber also participates in the ARC project as Industry Quad Member.

3. **FunctionBay, Inc. (PI: 100%), $40K, August 2013 – July 2014.** This research focuses on developing high-fidelity ANCF shear deformable beam and shell elements for a commercial general-purpose multibody dynamics simulation software. ANCF shear deformable elements are developed and compared with those of commercial software such as RecurDyn and ANSYS in terms of accuracy and computational efficiency. This leveraged funding allows PI and his team to purchase commercial software for use in conducting the benchmark test of the ANCF shear deformable composite shell element for the tire modeling under the ARC project.

Publications, Presentations, Copyrights, Patents or other Tech Transfer:

**Journal Papers**


Conference Papers


Other publications


Presentations


**Tech Transfer**

Technology transfer to TARDEC was accomplished successfully by transferring the physics-based deformable tire-soil interaction simulation capabilities implemented in our multibody dynamics code (IMBD) to the open-source multi-physics off-road mobility software Chrono used by TARDEC. This technology transfer allows TARDEC researchers and engineers to develop their own high-fidelity flexible tire and continuum-based soil models for vehicle performance evaluations on deformable terrains using the approach developed and validated in this study. Chrono software has been supported by DOD through Rapid Innovation Fund (RIF) - Army Research Office and Computational
Research and Engineering Acquisition Tools and Environments program for Ground Vehicles (CREATE-GV).

Honors, Awards, Keynote/Plenary and Named Lectures, Special Memberships:

Awards

Excellence in Oral Presentation Award, Society of Automotive Engineers (SAE), 2016.

Invited talks


