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Experimental testing of an off-road instrumented tire on soft soil

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Abstract

This study enhances the understanding of pneumatic tire–soft soil interaction through experimental work designed to investigate the effect of individual and combinations of tire/soil parameters on the tire/soil behavior. Its outcomes provide significant information to tire manufacturers, to users (for operating conditions selection), and to researchers (for modeling parameters and validation data).

To support the development of the Hybrid Soft Soil Tire Model (HSSTM), funded by the Automotive Research Center (ARC), experimental work has been performed on the Terramechanics Rig at AVDL. Although separate publications detail the HSSTM, a short description of the model and its capabilities is also included here. The rig provides a well-controlled environment and ensures repeatable testing conditions. A wireless sensory system that measures tire deflection has been developed and employed for accurate estimation of wheel sinkage. The data collected indicated that, by increasing the soil compaction or the normal load, or by decreasing the inflation pressure results in a higher normalized drawbar pull. The combined effect of increase in soil compaction and decrease in inflation pressure yields an even higher normalized drawbar pull. The sinkage increased dramatically with the slip ratio, growing to values 3–4 times larger at high slip versus lower slip ratios.

Keywords: Terramechanics; Tires; Soft soil; Mobility; Tire instrumentation; Test rig; Sinkage measurement; Slip; Drawbar pull

1. Introduction

Substantial effort has been ongoing at Virginia Tech to model tires operating on deformable terrain [1–10]. In support of the development of the Hybrid Soft Soil Tire Model (HSSTM), under the auspices of the Automotive Research Center (ARC), a U.S. Army Center of Excellence for Modeling and Simulation of Ground Vehicles, experimental work has been performed on the indoor single-wheel Terramechanics Rig at AVDL, to identify model parameters, as well as to collect validation data.

Through the years, many different approaches have been taken by various researchers to investigate and model traction performance affected by several tire properties, terrain, and operational conditions. Confirmed test methods can be learned and adapted to insure that proper techniques are applied to the work of this study; such past studies include slip control methods and starting conditions for a single wheel tester (SWT) [11] and controlled pull tests for a wheeled robot [12]. Although the work presented here revolves around the use of an SWTs, studies done on both SWTs and instrumented vehicles are reviewed, not only for their test methodologies, but also to learn how they considered and how they measured terrain conditions.

Common parameters of interests in tire–soil interaction tests are normal load (or wheel load) [13], tire inflation pressure [13–16], vehicle speed, and soil compaction [13].

In all tire–soil interaction studies, great consideration was put into the soil conditioning to maintain repetitive

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conditions, whether done by hand [12,16,17] or with equipment build for a specific purpose [13,16,18–21].

Reviewing experimental tire–soil testing studies, a common trend is seen in considering tire parameters (such as wheel slip, normal load, and inflation pressure), and their impact on the drawbar pull and the tire sinkage [22–23]. Soil compaction effects are noted as well. Moreover, great emphasis is placed within each study on establishing a systematic process of conditioning the soil before each test run.

1.1. Tire instrumentation

Understanding tire deformation on soft soil can aid in measuring the wheel sinkage, as it is difficult and not accurate to visually observe sinkage depth, in real time, and to determine how the rut of the soil differs from the actual wheel sinkage. Tire instrumentation has been a growing field, and the measurement sensors are improving with advancements in technology. As a great portion of this study focuses on tire instrumentation, understanding what has been done and what technologies yield the best results are imperative to significant tire instrument development.

Various sensor technologies have been used in the past to collect different types of data, such as the following:

- Pressure monitoring.
- Tread deformation [24–28].
- Carcass deflection [29–37].
- Estimation of tire–road friction [24,25,27].
- Estimate of tire forces [29,32,35].
- Estimation of slip angle and slip ratio [30–32,35].
- General tire health, etc. [27,29].

The tire sensor technologies reviewed had common challenges: avoiding disturbing the natural tire stiffness, packaging the instrument into a small size, data transmission, and power management. Depending on the type of tire (e.g., agricultural or passenger vehicle), there is a space constraint when one wants to place instrumentation inside the tire. Because of the tire rotation, using wires to collect data from a sensor can be difficult. Thus, many approaches have gone completely wireless or used slip rings, which often have speed limitations. Lastly, most sensors require power, so, similar to the data transmission challenge, various forms of powering a tire sensor system (whether it be wired or battery operated) are explored. All of these issues were considered for the tire sensor system developed in this study.

2. Indoor single wheel tester

The main platform used to conduct the experiments of this study is the Terramechanics Rig at the Advanced Vehicle Dynamics Lab (AVDL) at Virginia Tech [38–40]. The rig is a single-wheel tester that uses two separate motors to control wheel speed and slip of a tire that drives over a 7.62 m long soil bin. The carriage of the rig that houses the tire is shown in Fig. 1. The main instrument used on the rig is a Kistler P650 6-axes wheel hub measurement systems, which measures all moments and forces caused by the tire–terrain interaction.

Moreover, the rig has active normal load control to keep wheel load variation at less than 3% difference from the target value. The load is applied with two pneumatic air springs that vary in air pressure and is controlled with an electro-pneumatic control valve that can hold several open and close positions proportional to an input voltage signal. Input from the wheel hub sensor is used in the normal load control system. Additionally, the rig was developed to fit several tire sizes that can be set to ±25° in toe and from 0° to 6° in camber angle. However in this study, the tire was kept at a neutral toe and camber angle position.

3. Development of a tire deflection measurement system

Tire sinkage was of great interest to the study, so a new tire instrumentation system was developed to measure tire deflection in real-time and estimate maximum tire sinkage. Additionally, the Terramechanics Rig lacks rolling radius measurement. This is especially important as this parameter is required to accurately control wheel speeds to reach desired slips. Consequently, the rig lacks the capability of accurately measuring actual wheel sinkage, as it can only measure vertical wheel displacement; therefore, supplemental instrumentation methods were sought out to enable wheel sinkage measurement capabilities to the Terramechanics Rig.

The design of the instrument had to take into account many factors in order to provide rich data for the conditions of the Terramechanics Rig. From the technologies used for tire deflection measurements discussed in the literature review, the non-contact instruments, such as ultrasonic and optical sensors, were favored considerably to avoid interference with tire deformation. Due to the relatively small path for tire–soil testing in the rig, getting more

Fig. 1. Terramechanics Rig filled with silty sand and fitted with off-road tire.