On-Road Visualizations for Suspension Tuning of a Race Car

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Abstract. *The objectives of this study are to investigate and propose a new method of using visualization for measuring the dynamic behavior of a race car which corresponds to the tuning of the suspension system. All investigations were conducted on the race car called the "Student Formula CMU F-712", which was strictly constructed following the 2012 Formula SAE Rules. The behavior of this race car according to variations of the rear tire's pressures and rear cambers were visualized to evaluate the optimized suspension system's setup values. These values were suited for drag and skid-pad events. The type of front and rear suspensions of the race car was unequal length A-arm double wishbone. The vibrating force was transferred through push rods and bell cranks to shock absorbers and springs. Digital still cameras were used to capture the car's behavior and analyses performed from these pictures. It can be concluded that the on-road visualization is acceptable for measuring the dynamics of the race car corresponded to the tuning of the suspension system. The visualization methods used were the pitch angle of the car during launching and the outside rear camber and roll angle of the car during turning. Results obtained from the visualizations were compared with the results obtained from quantitative and qualitative tests to validate the analysis. It was found that very good agreement was archived.*

Keywords: Visualization, Suspension tuning, Double wishbone, Camber, Roll angle

1. Introduction

The suspension system consists of mechanical parts whose primary function is to isolate the car's structure from shock loading and vibration due to irregularity of the road surface. Moreover, it must do this without impairing the stability, steering, or general handling qualities of the vehicle. It can meet these requirements by the use of flexible elements, dampers, and mechanical linkages; such as, springs, stabilizer bars, shock absorbers, tires, wheels, wheel hubs, upright arms, linkages, joints, etc. [1]. The suspension system's parts can be generally adjusted, such as the wheel alignment, kingpin inclination, spring stiffness, shock absorber damping rate, tire pressures, especially in race cars. These are for optimal vehicle stability during driving which directly affects speed. This directly affects the competition result and also the safety of the driver. There are a number of optimized designs on suspension systems; such as, (a) geometrical and shape analysis which is used for suspension system design [2-4], (b) dynamic analysis which is important for the dynamics and response of the suspension systems [5-7], and (c) strength analysis which is a useful tool for selecting suitable material and sizing of the suspension systems [2].

Although the suspension system has been very well designed and manufactured by the above mentioned methods, a consequent problem is how the suspension system can be tuned to suit with each different driving characteristic. Although the dynamic analysis can lead to a solution, a great number of outside factors can cause the analysis to become very complicated. Therefore, another method for tuning the suspension system, which is not so complex, is desired among the automotive community. Transducers are installed on each part of the suspension system [8] in order to measure the dynamic properties, such as, linear and angular accelerations, forces and torques. The designer takes these measured values to be a guideline for tuning the suspension system. The high cost of the instruments and the large amount of equipment are the major disadvantages to this method. Thus, this method cannot be reasonably used by small design units which rarely have high capital, such as the "CMU Auto Club" of the Faculty of Engineering, Chiang Mai University, where the Student Formula is designed, constructed and competes in the annual TSAE Student Formula Challenge [9] organized by the Society of Automotive Engineers Thailand.

The requirement for tuning the suspension system within a limited budget, a new measurement concept called 'visualization' in which physical behaviors are visualized and recorded is therefore proposed in this study. The objective is to investigate the possibility of using the visualization for measuring the dynamics of the race car which corresponds to the tuning on suspension system. Results obtained from this study will be useful for evaluating the car's behavior and this usefulness will apply to all levels in the automotive development including industrial complexes, companies, universities, colleges and private or local garages.

2. Experimental Setup and Procedure

All investigations were conducted on the race car "Student Formula CMU F-712" which was strictly constructed following the 2012 Formula SAE Rules [10] as shown in Fig. 1. The front and rear suspensions were of the type unequal length A-arm double wishbone. The vibrating force was transferred through push rods and bell cranks to shock absorbers and springs (Fox, DHX RC 4.0). The camber and toe, shock absorber's damping rate and tire pressure could be adjusted freely between the front and rear suspensions. The controlled parameters for the race car were as follows: front track of 1,250 mm, rear track of 1,225 mm, wheelbase of 1,650 mm, curb weight including a driver of 390 kg, static weight distribution between the front and rear of 44:56, aluminum alloy wheels (Lenso, Raiden, 13 x 7.5 inch), drag slick tires (Hoosier, R25B, 20 x 7.5 inch), 599-cc 4-cylinder 4-stroke gasoline engine with manual transmission (Suzuki, GSX-R, Model year 2007), chain and sprocket transmission with a final ratio of 4.076:1, and 1.5-ways viscous limited slip differential (Subaru, Impreza 2.0L). The experiment was divided into 2 parts as (a) the visualization to investigate the car's behavior according to rear tire's pressures for a drag event and (b) the visualization to investigate the car's behavior according to rear cambers for a skid-pad event. Details of each experiment are described as follows.

Fig. 1: Student Formula CMU F-712

2.1 Experiment on the effect of the rear tire pressures

For this section, the additional controlled parameters were as follows: the front tire pressure was 20 psi, the front and rear shock absorber's damping rate were 75% and 50% of the maximum respectively, the front and rear cambers and toes were 0˚ and 0 mm respectively. The tire pressure and camber angle were measured by a mechanical bourdon pressure gauge and a handheld wheel-alignment tester (Banzai, MB-40E, ±0.5^{o} accuracy), respectively. The investigation was conducted by varying the rear tire pressure from 4 to 20 psi in order to understand which value suits for the launching and accelerating in a drag event by considering the pitch angle of the race car which was recorded by a digital still camera (Nikon, D7000, 16.2 Mpixel). This was located at the start line of the drag strip as shown in Fig. 2. The experimental procedure began when the car's nose reached the start line and the engine speed was locked at 8,000 rpm. The digital camera consequently took continuous pictures with a speed of 6 frames per second. The clutch was instantly released to launch the car and the car then was fully accelerated to the finish line and each gear was shifted up constantly at 8,000 rpm. The pitch angle of the car in this study was defined as an angle between (i) the connecting line from the lowest part of the nose of the car taken at just-before launching (0th second) to the one taken at just-after launching (1/6th second) and (ii) the horizontal plane as shown in Fig. 3. The elapsed time from the start to the finish line was simultaneously recorded. Also the well-trained driver was interviewed and his opinions were reported in an evaluation form and used as qualitative data in further analysis. The experimental procedure was repeated until all of the rear tire pressures were investigated. Finally, the pitch angles, elapsed times and the opinions of the driver obtained from all experiments were simultaneously analyzed for the effect of the rear tire pressures on the race car's launching. The possibility of using the visualization for the race car's dynamic performance was investigated.

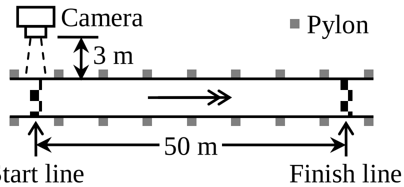


Fig. 2: Drag strip and camera's location

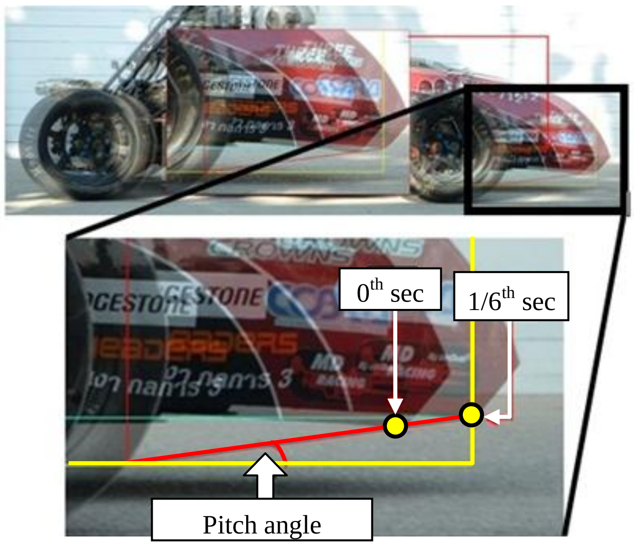


Fig. 3: Measurement of the pitch angle

2.2 Experiment on the effect of the rear cambers

For this part, the following were the additional controlled parameters: front and rear tire pressures, shock absorber damping rates and toes of 18 psi, 75% of the maximum and 0 mm respectively. The front camber was -2^{o}. The investigation was conducted by varying the rear camber from 0^{o} to -3^{o} in order to understand the optimum stability in the skid-pad event by considering the outside rear camber and roll angles of the race car which was recorded by two digital still cameras (Nikon, D7000, 16.2 Mpixel) located beside the skid-pad track as shown in Fig. 4.

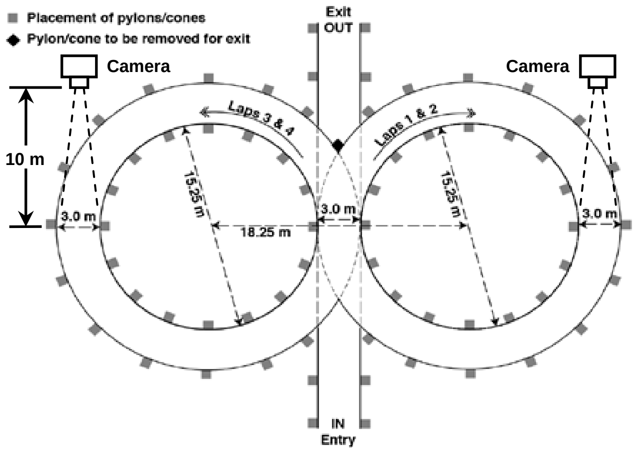


Fig. 4: Skid-pad track and camera location (modified from [10])

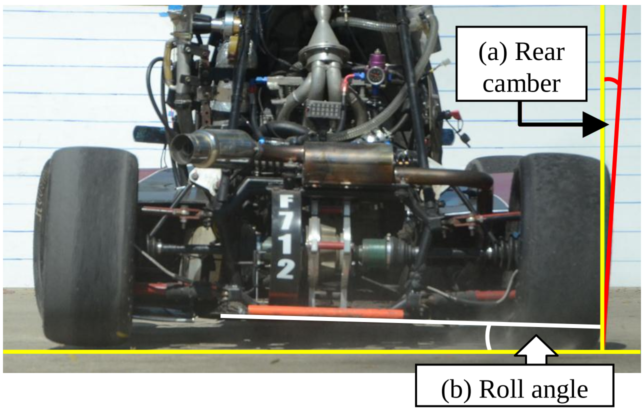


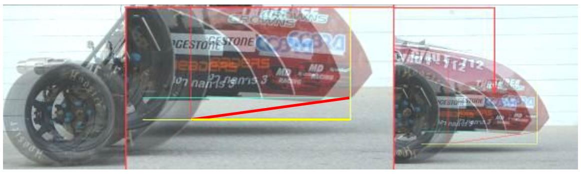
Fig. 5: Measurement of angles

The experimental procedure began when the car's nose reached the start line and the engine speed was locked at 6,000 rpm and then launched. The car was driven in clockwise and counter-clockwise directions, two laps each and the engine speed was constantly controlled at 6,500 rpm in second gear until the car reached the finish line. The outside rear camber and roll angle which were measured from an angle between the rearmost frame and the horizontal plane, were captured as shown in Fig. 5 (a) and (b), respectively. Experimental procedure was repeatedly done until all variable parameters were investigated. Finally, outside rear cambers, roll angles, elapsed times and well-trained driver's opinions reported in an evaluation form obtained from all experiments were simultaneously analyzed for the effect of the rear cambers on the race car's stability. The possibility of using the visualization for the race car's dynamic investigation was also evaluated.

3. Results and Discussions

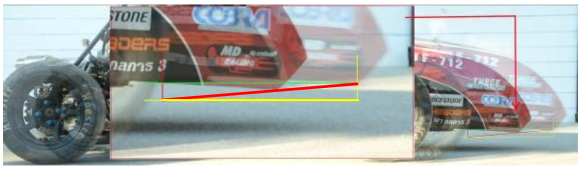
3.1 Investigating the behavior from rear tire pressure visualization

It was found from the data that when rear tire's pressure increased from 4 to 8, 12, 16, and 20 psi, the pitch angle of the car decreased from 7.59^{o} to 7.23^{o}, 4.97^{o}, 4.40^{o}, and 2.26^{o}, respectively. Pictures of the 0th and 1/6th second after launching taken from each experiment are shown in Fig. 6 (a) to (e).



(a) 4 psi, pitch angle = 7.59^{o}

(b) 8 psi, pitch angle = 7.23^{o}



(c) 12 psi, pitch angle = 4.97^{o}

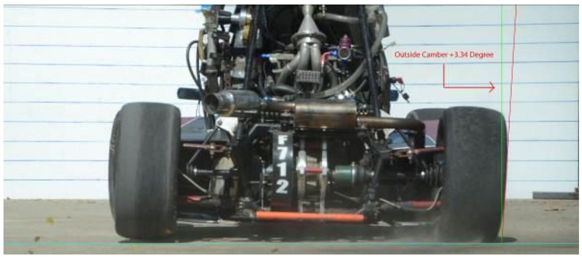
(d) 16 psi, pitch angle = 4.40^{o}

(e) 20 psi, pitch angle = 2.26^{o}

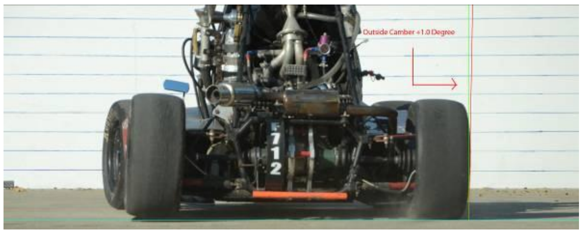
Fig. 6: Car's behavior according to rear tire pressures

The pitch angle of the car is affected by the acceleration or deceleration exerting on the car. Note that only acceleration is focused on in this study. When the car's velocity increases after a sum of longitudinal forces acting on the car is higher than zero, the inertia force will be exerted on the car. This causes a higher portion of car's weight to be transferred to the rear. While the weight is transferring rearward, the rear suspension is bumping and the front one is rebounding. This causes a change in the pitch angle. In general, an increase in the pitch angle implies that the weight exerting on rear drive wheels has increased and friction between tires and road surface also increased. This causes a decrease in slippage of the tires and an increase in the acceleration during launching. In addition, since the shock absorber's damping rate and spring stiffness were constantly controlled for all the experiments, the pitch angle will increase directly proportional to the transferring weight and the acceleration's magnitude during launching. For this reason, it can be concluded that the rear tire's pressure of 4 psi causes the best launching behavior of the Student Formula CMU F-712 since the maximum pitch angle of 7.59^{o} is archived. This is a result from the most rearward weight transfer which subsequently causes the highest launching acceleration or the lowest slippage of the drive wheels.

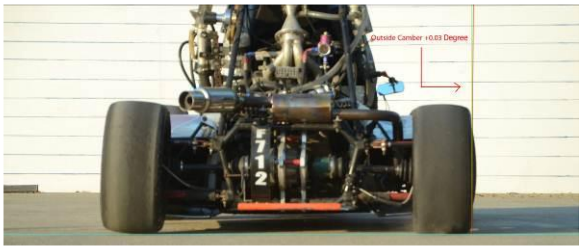
This conclusion on the suitable rear tire's pressure can be validated with quantitative results by comparing the elapsed time in the drag strip. It was found that when the rear tire's pressure increased from 4 to 8, 12, 16, and 20 psi, the elapsed time increased from 3.54 to 3.57, 3.59, 3.72 and 3.84 seconds respectively. It can be seen that the rear tire's pressure of 4 psi is the best value since it causes the lowest elapsed time. Moreover, the visualized and quantitative results agree well with qualitative data which is the driver's feedback. It was reported when the rear tire's pressure was 4 psi that, the rear suspension obviously bumped and the drive wheels instantly created good traction. Nevertheless, after the rear tire's pressure increased, the rear suspension was found to be stiffer, and increased slippage of the drive wheels was sensed.



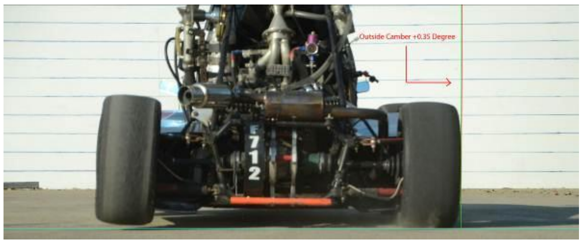
(a) 0^{o}, rear camber = +3.34^{o}, roll angle = 1.77^{o}



(b) -1.0^{o}, rear camber = +1.00^{o}, roll angle = 0.88^{o}



(c) -2.0^{o}, rear camber = +0.03^{o}, roll angle = 0.31^{o}



(d) -3.0^{o}, rear camber = +0.35^{o}, roll angle = 1.10^{o}

Fig. 7: Car's behavior according to rear cambers

3.2 Investigating the behavior from rear camber visualization

It was found that when the rear camber decreased from 0^{o} to -1.0^{o}, -2.0^{o}, and -3.0^{o}, the outside rear camber during turning changed from +3.34^{o} to +1.00^{o}, +0.03^{o}, and +0.35^{o}, respectively, and roll angle changed from 1.77^{o} to 0.88^{o}, 0.31^{o}, and 1.10^{o}, respectively. Pictures taken from each experiment are shown in Fig. 7 (a) to (d).

This dynamic behavior results from the relationships between lateral weight transfer, body roll and camber change during turning. Camber angle equals the inclination of the wheel with respect to the vertical plane. It takes a positive value when the top of the wheel leans outward from the car centerline [11]. Generally, a tread area of the tire will fully contact with road surface when the camber is 0^{o}. For a case of driving in a straight line, zero camber causes the best grip and stability.

Nevertheless while the car is turning, a centrifugal force is exerted on the center of gravity (CG) of the car in the lateral direction outside of the car. This causes the body to roll and the force will consequently transfer through upper A-arm and wheel located on the outside of the car. According to this force, the upper portion of the wheel is pushed outward and then the camber will change to be more positive. The tread area of the tire fully contacting with the road decreases and the grip will decrease compared to the former case. Thus, stability during turning decreases. For this reason, the cambers of race cars driven in curved tracks such as skid-pad or full course tracks, including general passenger cars are initially adjusted to have a negative value. Due to this setup, outside cambers will not change to positive while the cars are turning. The visualization showed that when the rear camber decreased from 0^o to -2.0^o; while the race car was on the curve, the outside rear camber decreased from $+3.34^o$ to $+0.03^o$ (tread area of the tire almost fully contacted with the road surface). This change causes an increase in grip of the drive wheel and a decrease in oversteer. Thus, the slip angle of the tire will decrease [11, 12]. In general, if a slip angle decreases, the tire will create higher grip to resist more centrifugal force. The stability during turning will increase. In addition to the decrease in outside camber, wheel and upper A-arm will support the body to roll decreasingly. Evidence can be seen from the visualization that the roll angle decreased from 1.77^o to 0.31^o. After the rear camber decreased from -2.0^o to -3.0^o, a change in physical behavior was seen as described above. The outside wheel had a higher grip and lower slip angle. In general, if the slip angle decreases beyond a certain value, the oversteer will disappear. This causes the outside wheel to have excessive grip during turning. The contacting point between the tire and road surface will be equivalent to a rotating point. Simultaneously, the high magnitude of the lateral weight transfer causes the body to roll increasingly and the inside wheel will subsequently lift. It could be seen from the visualization that the roll angle suddenly increased from 0.31^o to 1.10^o. From this viewpoint, power transmission to a road during turning rapidly drops along with the stability. These behaviors are affected by the jacking force which increases as the roll center (RC) locates closer to the CG. For the Student Formula CMU F-712, the roll center was designed to be located near the CG since the roll moment and roll angle of the car during turning will decrease [12].

From the visualization, it can be concluded that the rear camber of -2.0^o is the best value for the Student Formula CMU F-712 being in the skid-pad event since the tread area of the outside tire fully contacts with a road surface. The conclusion can be validated with quantitative result by comparing to the elapsed time in the skid-pad track. It was found that when rear camber decreased from 0^o to -1.0^o, -2.0^o, and -3.0^o, the elapsed time changed from 27.10 to 26.42, 26.00, and 26.50 second, respectively. It can be seen that when the rear camber is -2.0^o, results in the lowest elapsed time. Moreover, the visualized and quantitative results very well agree with qualitative data from the driver's feedback. It was reported when the rear camber was -2.0^o that the car rarely had oversteer and the car could turn in the track with constant steering wheel angle. Nevertheless, after the rear camber increased, the oversteer was observed to increase, thus, the driver had to correct the direction of the car for the entire track.

3.3 Impacts and suggestions

The visualization for measuring the dynamic response of the race car corresponded to the tuning of the suspension system proposed in this study is expected to be a new interesting tool which can help engineers, mechanics, students and people interested in automotive engineering in the suspension system tuning and design. An advantage of this method is that, the instruments are inexpensive, testing procedure is not complex and the dynamic behavior of the car at a specified time can be directly investigated. However, it should be reminded that error in the visualization is always higher than error in the quantitative test. Therefore, a suitable method should be carefully chosen to match with the objective of each test.

4. Conclusion

The study entitled on-road visualization for suspension tuning of a race car has been conducted. Good agreements of results were obtained from the visualized, quantitative and qualitative experiments. It can be concluded that the on-road visualization can be used for measuring the dynamics of the race car corresponded to the tuning on the suspension system. The suitable visualization to investigate the car's behavior according to the rear tire pressures for drag event is an analysis of the pitch angle of the car during launching. It is found that the higher pitch angle, the better launching. In this case, when the rear tire's pressure was 4 psi, the maximum pitch angle of 7.59^o was achieved which proved to be the best for launching. Moreover, the visualization to investigate car's behavior according to the rear cambers for skid-pad event is an analysis on the outside rear camber and roll angle of the car during turning. It is found that when the outside rear camber approaches zero and the roll angle was the lowest, the car had the best stability during turning. For this case, the best result was obtained when the rear camber was -2.0^o, since the outside rear camber mostly approached zero as of $+0.03^o$ and the roll angle was a minimum of 0.31^o.

5. Acknowledgement

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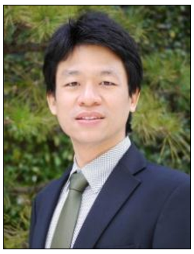

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