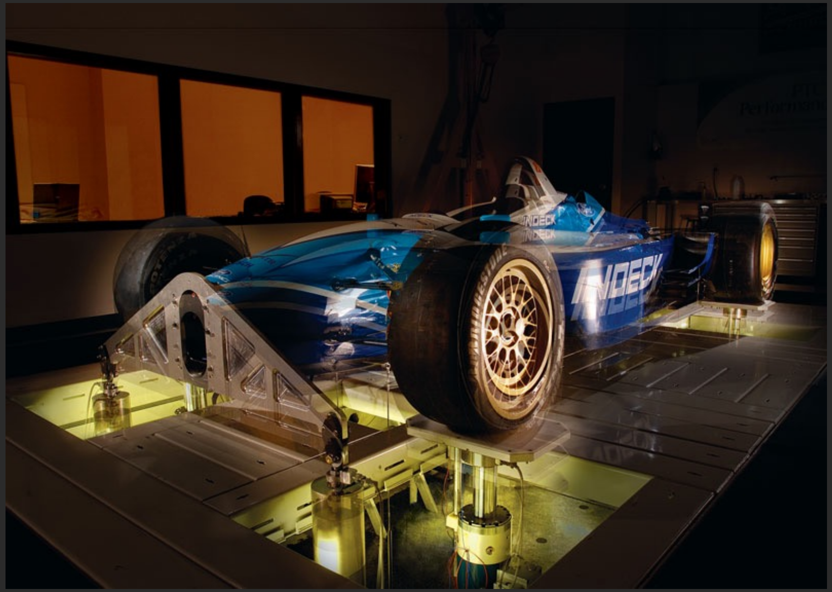
Final Assignment

Suspension shaker rig

A suspension shaker rig is a chassis test machine that applies loads to the vehicle through hydraulic actuators in order to analyse the vehicle response. There are two types of rigs: 4-post or 7-post 4-post rigs apply vertical loads to the contact patches using four hydraulic actuators, one per vehicle corner., to simulate the road inputs. In addition, 7-post rigs apply extra loads to consider the aerodynamic forces.

7-post rigs are widely used in racing teams to optimise and tune the suspension before arriving at a racetrack. The typical goal is to minimise the contact patch load variation using as an input the racetrack profile.

The final assignment of the Vehicle Dynamics Modelling and Simulation course consists on building a suspension shaker rig that will also account for the lateral acceleration of the vehicle to make the most out of the optimisation.



Source: *www.arcindy.com*

Final Assignment
Suspension shaker rig

Assignment:

- Build a suspension shaker rig using the vertical dynamics out-of-plane model equations, considering as inputs:
    - Vehicle velocity
    - Lateral acceleration
    - Road profile FL
    - Road profile FR
    - Road profile RL
    - Road profile RR

Final Assignment

Suspension shaker rig

Formula vehicle parameters (1/2):

Vehicle parameters - dimensions		
Parameter		Value
L	Wheelbase [m]	3.50
h	CoG height [m]	0.20
a	Sprung mass CoG front distance [m]	1.80
t_f	Front Wheel track [m]	1.75
t_r	Rear Wheel track [m]	1.85
r	Wheel radius [m]	0.375
h_{rcf}	Front roll centre height [m]	0.04
h_{rcr}	Rear roll centre height [m]	0.06
h_{rc}	Roll centre height [m]	0.05

Vehicle parameters – mass and inertia		
Parameter		Value
m	Mass [kg]	850.00
m_{usf}	Front corner unsprung mass [kg]	15.00
m_{usr}	Rear corner unsprung mass [kg]	17.50
I_{xx}	Roll inertia [kgm^2]	300.00
I_{yy}	Pitch inertia [kgm^2]	1350.00

Aerodynamics		
Parameter		Value
A	Frontal area [m^2]	1.25
c_z	DF coefficient	1.00
ρ	Air density [kg/m^3]	1.225

Final Assignment
Suspension shaker rig

Formula vehicle parameters (2/2):

Suspension parameters		
Parameter		Value
k_{sf}	Front spring stiffness [N/m]	67,500.00
C_{df}	Front damping coefficient [Ns/m]	1,400.00
k_{ARBf}	Front ARB stiffness [Nm/rad]	5,000.00
k_{sr}	Rear spring stiffness [N/m]	100,000.00
c_{dr}	Rear damping coefficient [Ns/m]	1,800.00
k_{ARBr}	Rear ARB stiffness [Nm/rad]	1,000.00
k_{tyre}	Tyre vertical stiffness [N/m]	400,000.00

Final Assignment
Suspension shaker rig

Equations summary (1/5):

- Sprung mass (3 DOF):
  - Vertical: $F_{s.fl} + F_{s.fr} + F_{s.rl} + F_{s.rr} + F_{d.fl} + F_{d.fr} + F_{d.rl} + F_{d.rr} - m_s \cdot g - F_{DF} = m_s \cdot \ddot{z}_s$
  - Pitch: $-a \cdot (F_{s.fl} + F_{s.fr} + F_{d.fl} + F_{d.fr}) + b \cdot (F_{s.rl} + F_{s.rr} + F_{d.rl} + F_{d.rr}) = I_{yy} \cdot \ddot{\theta}$
  - Roll: $(F_{s.fl} - F_{s.fr} + F_{d.fl} - F_{d.fr}) \cdot {}^{t_f}/_2 + (F_{s.rl} - F_{s.rr} + F_{d.rl} - F_{d.rr}) \cdot {}^{t_r}/_2 + m_s \cdot a_y \cdot (h_{COG} - h_{RC}) - (\Gamma_{ARB.f} + \Gamma_{ARB.r}) = I_{xx} \cdot \ddot{\phi}_s$

Final Assignment

Suspension shaker rig

Equations summary (2/5):

- Unpsrung masses (4 DOF):
  - FL: $F_{t.fl} - F_{s.fl} - F_{d.fl} - m_{us.f} \cdot g + \frac{\Gamma_{ARB.f} + m_s \cdot \frac{b}{L} \cdot a_y \cdot h_{RC.f} + 2 \cdot m_{us.f} \cdot a_y \cdot h_{USM.f}}{t_f} = m_{us.f} \cdot \ddot{z}_{us.fl}$
  - FR: $F_{t.fr} - F_{s.fr} - F_{d.fr} - m_{us.f} \cdot g - \frac{\Gamma_{ARB.f} + m_s \cdot \frac{b}{L} \cdot a_y \cdot h_{RC.f} + 2 \cdot m_{us.f} \cdot a_y \cdot h_{USM.f}}{t_f} = m_{us.f} \cdot \ddot{z}_{us.fr}$
  - RL: $F_{t.rl} - F_{s.rl} - F_{d.rl} - m_{us.r} \cdot g + \frac{\Gamma_{ARB.r} + m_s \cdot \frac{a}{L} \cdot a_y \cdot h_{RC.r} + 2 \cdot m_{us.r} \cdot a_y \cdot h_{USM.r}}{t_r} = m_{us.r} \cdot \ddot{z}_{us.rl}$
  - RR: $F_{t.rr} - F_{s.rr} - F_{d.rr} - m_{us.r} \cdot g - \frac{\Gamma_{ARB.r} + m_s \cdot \frac{a}{L} \cdot a_y \cdot h_{RC.r} + 2 \cdot m_{us.r} \cdot a_y \cdot h_{USM.r}}{t_r} = m_{us.r} \cdot \ddot{z}_{us.rr}$

Final Assignment

Suspension shaker rig

Equations summary (3/5):

- Spring:
  - FL: $F_{s.fl} = F_{0.fl} + k_{s.fl} \cdot \left(z_{us.fl} - z_s + \theta \cdot a - \emptyset_s \cdot {}^{t_f}/_{2}\right); F_{0.fl} = m_s \cdot g \cdot \frac{b}{L} \cdot \frac{1}{2}$
  - FR: $F_{s.fr} = F_{0.fr} + k_{s.fl} \cdot \left(z_{us.fl} - z_s + \theta \cdot a + \emptyset_s \cdot {}^{t_f}/_{2}\right); F_{0.fr} = m_s \cdot g \cdot \frac{b}{L} \cdot \frac{1}{2}$
  - RL: $F_{s.rl} = F_{0.rl} + k_{s.rl} \cdot \left(z_{us.rl} - z_s - \theta \cdot b - \emptyset_s \cdot {}^{t_r}/_{2}\right); F_{0.rl} = m_s \cdot g \cdot \frac{a}{L} \cdot \frac{1}{2}$
  - RR: $F_{s.rr} = F_{0.rr} + k_{s.rr} \cdot \left(z_{us.rr} - z_s - \theta \cdot b + \emptyset_s \cdot {}^{t_r}/_{2}\right); F_{0.rr} = m_s \cdot g \cdot \frac{a}{L} \cdot \frac{1}{2}$
- ARB:
  - Front: $\Gamma_{ARB.f} = k_{ARB.f} \cdot \left(\emptyset_s - \frac{z_{us.fl} - z_{us.fr}}{t_f}\right)$
  - Rear: $\Gamma_{ARB.r} = k_{ARB.r} \cdot \left(\emptyset_s - \frac{z_{us.rl} - z_{us.rr}}{t_r}\right)$

Final Assignment

Suspension shaker rig

Equations summary (4/5):

- Damper:
  - FL: $F_{d.fl} = c_{d.fl} \cdot \left(\dot{z}_{us.fl} - \dot{z}_s + \dot{\theta} \cdot a - \dot{\emptyset}_s \cdot {}^{t_f}/_2\right)$
  - FR: $F_{d.fr} = c_{d.fr} \cdot \left(\dot{z}_{us.fr} - \dot{z}_s + \dot{\theta} \cdot a + \dot{\emptyset}_s \cdot {}^{t_f}/_2\right)$
  - RL: $F_{d.rl} = c_{d.rl} \cdot \left(\dot{z}_{us.rl} - \dot{z}_s - \dot{\theta} \cdot b - \dot{\emptyset}_s \cdot {}^{t_r}/_2\right)$
  - RR: $F_{d.rl} = c_{d.rr} \cdot \left(\dot{z}_{us.rr} - \dot{z}_s - \dot{\theta} \cdot b + \dot{\emptyset}_s \cdot {}^{t_r}/_2\right)$

Final Assignment

Suspension shaker rig

<u>**Equations summary (5/5):**</u>

- Tyre:
  - FL: $F_{t.fl} = k_{t.f} \cdot (z_{r.fl} - z_{us.fl})$; $z_{o\ t.fl} = \left(m_s \cdot g \cdot \frac{b}{L} \cdot \frac{1}{2} + m_{us.fl}\right) \cdot g / k_{t.f}$
  - FR: $F_{t.fr} = k_{t.f} \cdot (z_{r.fr} - z_{us.fr})$; $z_{o\ t.fr} = \left(m_s \cdot g \cdot \frac{b}{L} \cdot \frac{1}{2} + m_{us.fr}\right) \cdot g / k_{t.f}$
  - RL: $F_{t.rl} = k_{t.r} \cdot (z_{r.rl} - z_{us.rl})$; $z_{o\ t.rl} = \left(m_s \cdot g \cdot \frac{a}{L} \cdot \frac{1}{2} + m_{us.rl}\right) \cdot g / k_{t.r}$
  - RR: $F_{t.rr} = k_{t.r} \cdot (z_{r.rr} - z_{us.rr})$; $z_{o\ t.rr} = \left(m_s \cdot g \cdot \frac{a}{L} \cdot \frac{1}{2} + m_{us.rr}\right) \cdot g / k_{t.r}$

Final Assignment
Suspension shaker rig

Results presentation:

- To ease the correction of the module assignment, the following results should be presented.

1. Screenshot of the Simulink blocks build for the vehicle DOFs and component forces calculation:
    a. Sprung mass vertical
    b. Sprung mass pitch
    c. Sprung mass roll
    d. Unsprung mass FL vertical
    e. Unsprung mass FR vertical
    f. Unsprung mass RL vertical
    g. Unsprung mass RR vertical
    h. Spring FL
    i. Spring FR
    j. Spring RL
    k. Spring RR
    l. Damper FL
    m. Damper FR
    n. Damper RL
    o. Damper RR
    p. ARB front
    q. ARB rear
    r. Tyre FL
    s. Tyre FR
    t. Tyre RL
    u. Tyre RR

Final Assignment

Suspension shaker rig

Results presentation:

- To ease the correction of the final assignment, the following results should be presented.

2. Model verification steps:
   a. Static equilibrium: no suspension or tyre displacement if the model inputs are 0.
   b. Aero forces: suspension normal forces increase with the square of speed if we consider a ramp for the speed input.
   c. Load transfer: considering a ramp input for the lateral acceleration with constant velocity and no road input, the normal tyre load should increase due to the lateral load transfer. Check the values for $4m/s^2$ lateral acceleration.
   d. Suspension natural frequencies: heave and wheel hop natural frequencies using a constant amplitude velocity input for the road irregularities should be in line with hand calculations. Use a 0km/h speed to ensure starting from equilibrium.

Final Assignment

Suspension shaker rig

Applications of the suspension shaker rig model:

- Here you can find a couple of examples on the applicability of the suspension shaker rig model built in the final course assignment. This will not be evaluated as part of the course but you are encourage to share your work and progress in the discussion section.
  - Optimization of suspension spring and damper properties to minimise the tyre load variation under certain road inputs. Model enhancement: include the suspension installation ratios and the damper curves – Damper force = f(damper velocity).
  - Coupling of the bicycle model with the suspension shaker rig model to have a 10-DOF model for handling and comfort evaluation during early stages of development.
    - Bicycle model: Divide the front and rear axle lateral force as the summation of the left and right tyre lateral forces.
    - Bicycle model info received from suspension shaker rig: tyre vertical force – FL, FR, RL, RR.
    - Suspension shaker rig info received from the bicycle model: lateral acceleration.
    - Model inputs: Vehicle velocity, steering wheel angle, road roughness – FL, FR, RL, RR.