Large ACC Fan Gearbox Loads

D.N.J. Els, C.J. Van Rensburg, M.P. Venter

Stellenbosch University, South Africa

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Outline

1. Background
2. Data Measurement
   - Shaft speed
   - Shaft torsion
   - Fan torsion load
   - Shaft bending
3. Conclusions
4. Future Work

Background

ACC Fan Gearbox Load Measurements at the Medupi and Kusile Power Stations

A series of measurements were conducted on the ACC gearbox output shafts at the South African Medupi and Kusile power stations.

- These stations are new and comparable in size. Six dry cooled units, 6×794 MW total.
- Identical Hansen M4 ACC gearboxes.
- Medupi ACC induction motor start-up is direct online.
  Kusile employs a thyristors type soft-start.

Measurements as part of research project for SUMITOMO HEAVY INDUSTRIES, PTC Division, Global R&D Centre, Belgium.

Background

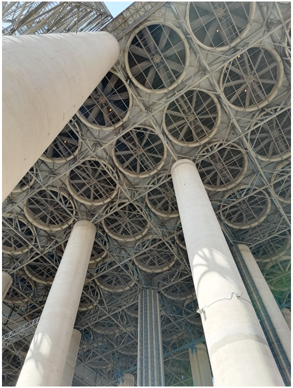
ACC Fan Gearbox Load Measurements at the Medupi and Kusile Power Stations

Bing Maps

Background

Kusile Power Stations

Wikipedia: Kusile



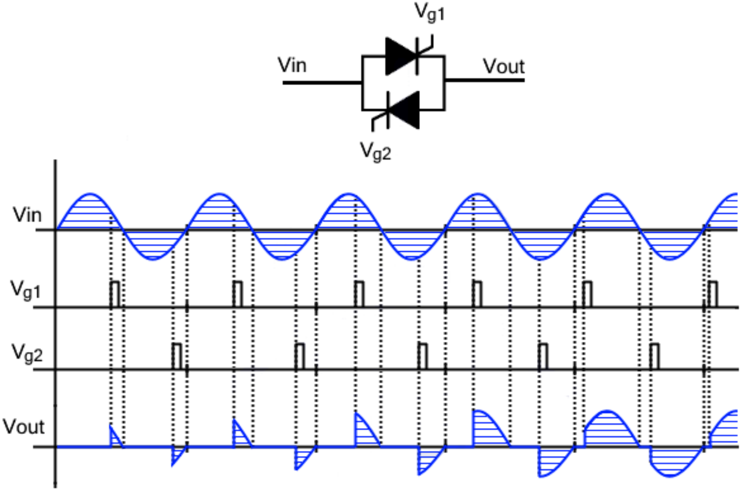
Medupi ACC

- **Fan:**
  34 ft Howden ELF 8 blades
  Hansen M4 ACC gearboxes
  } Test fan
- **Start up:**
  Direct

Kusile ACC

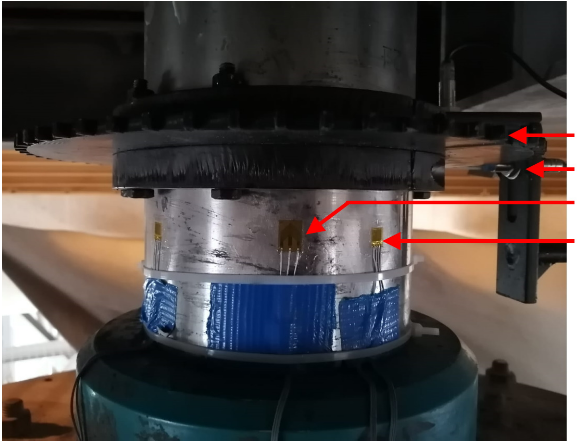
- **Edge Fans:**
  34 ft Howden ELF 8 blades
  Hansen M4 ACC gearboxes
- **Internal Fans:**
  34 ft Howden ENF 9 blades
  Hansen M4 ACC gearboxes
  } Test fan
- **Start up:**
  Thyristors type soft-start

Thyristor pair operation per phase of soft starter

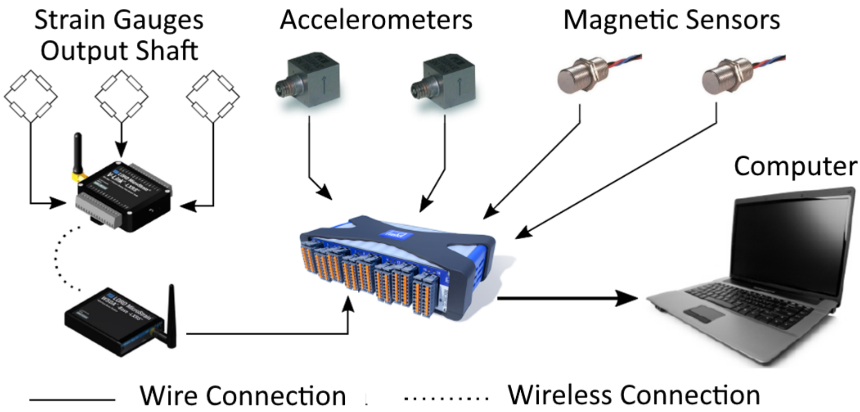


https://www.electricaltechnology.org/2020/08/soft-starter.html

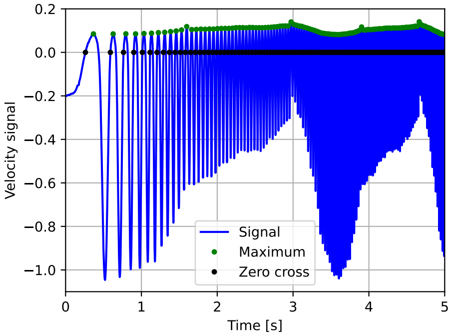
Measurement setup

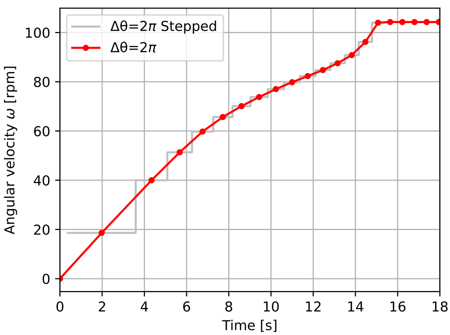


Measurement setup



Shaft speed calculation





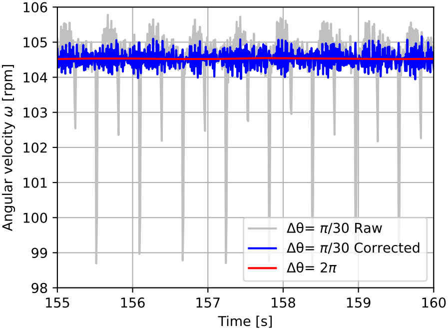
Find peaks

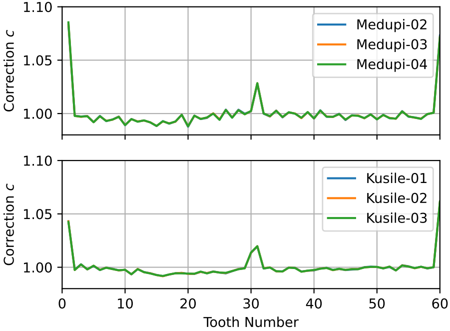
- Find max between zero crossings
- Fit parabola through 3 points around max and calc peak time τ_i.
- Max points are separated $\Delta\theta = 2\pi/n$

Calculate raw velocity

- Time difference: $\Delta\tau_i = \tau_{i+1} - \tau_i$
- Average velocity: $\omega_i = \Delta\theta/\Delta\tau_i$
- Midpoint time: $t_i = \tau_i + \Delta\tau_i/2$

Shaft speed calculation

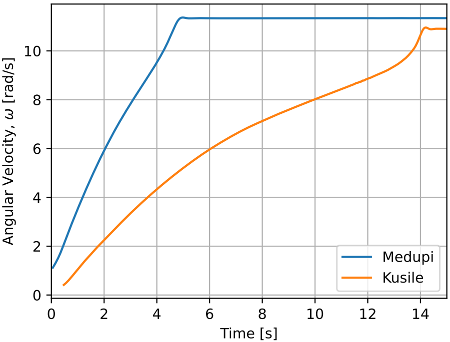


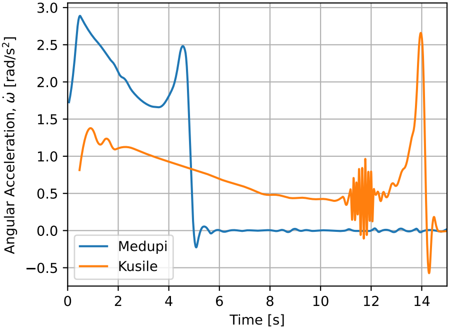


Correct for tooth wheel errors

- Every $n = 60$ point repeats. Assume accurate time difference for $\Delta\theta' = 2\pi$.
- Take $\Delta\tau'_j = \tau_{n(j+1)} - \tau_{nj}$ and $t'_j = \tau'_i + \Delta\tau'_j/2$. Calculate velocity $\omega'_j = \Delta\theta'/\Delta\tau'_j$.
- Calculate spline through $(t'_j, \omega'_j) \rightarrow \mathcal{S}'_\omega$ to obtain once per rotation velocity $\omega'(t) = \mathcal{S}'_\omega(t)$ at any time.
- Define correction factor c_k, $k = 1, 2, \ldots, n$ for every tooth.
- Minimize error $\epsilon(c) = \sum_{j=0} \sum_{k=1}^{n} [\mathcal{S}'_\omega(t_{jn+k}) - c_k \omega_{jn+k}]^2$ to obtain best c.
- Correct velocity $c_k \omega_{jn+k}$ cyclic for every tooth, $k = 1, 2, \ldots, n$ and $j = 0, 1, \ldots$

Shaft speed calculation

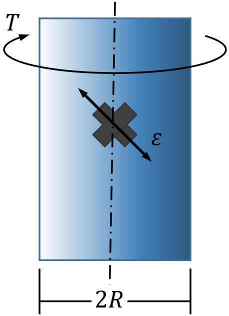




Start-up angular velocity and acceleration

- Fit smoothing spline through corrected velocity and time points $(t_i, \omega_i) \rightarrow \mathcal{S}_\omega$.
- Interpolate to obtain angular velocity $\omega(t) = \mathcal{S}_\omega(t)$
- Differentiate spline calculate to angular acceleration $\dot{\omega}(t) = d\mathcal{S}_\omega(t)/dt$

Shaft torsion



The torque strain gauges are fitted at an angle of 45° to the axis of the shaft. For a strain ε along the direction of the gauge the torque-strain relationship is

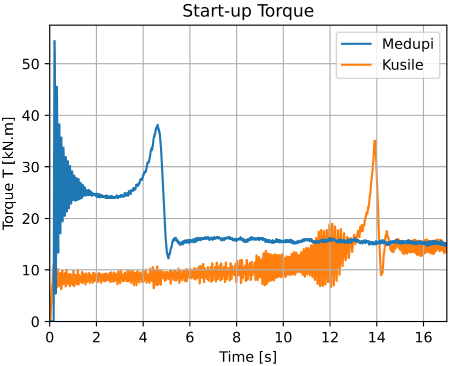
$$T = \frac{\pi E R^3}{2(1+\nu)} \cdot \varepsilon$$

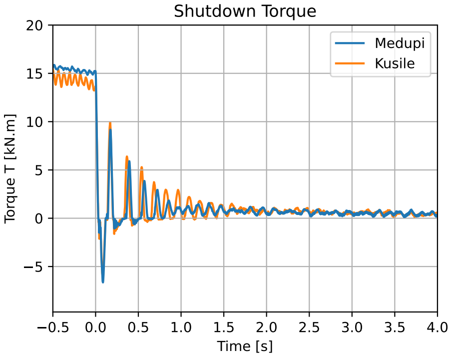
T	Applied torque	[N·m]
ε	Strain	[m/m]
$R = 65.75$ mm		Shaft radius
$E = 207$ GPa		Young's modules
$\nu = 0.29$		Poison's ratio

The gauge constant is then

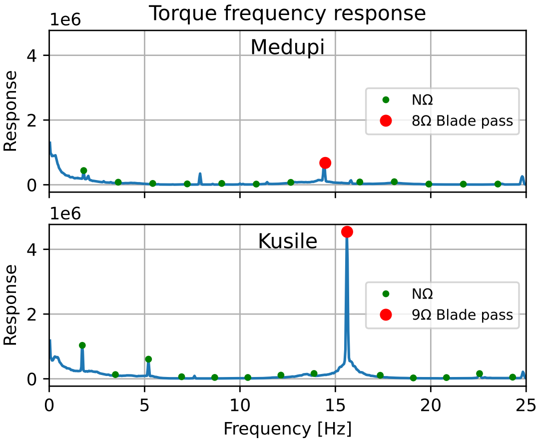
$$K_T = \frac{T}{\varepsilon} = \frac{\pi E R^3}{2(1+\nu)} = 72.205 \ \frac{\text{N·m}}{\mu\text{m/m}}$$

Shaft torsion





Shaft torsion



Find the average frequency response over a long time (3 hours in this instance) to smooth out noise

- FFT ($N_{\text{FFT}} = 2^{15}$, Han windowed)
- 50% overlap for successive FFT windows.
- Sample frequency $f_s = 1200$ Hz

Fan torsion load

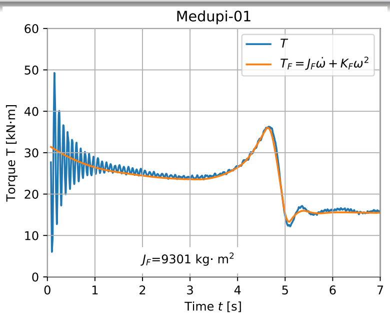
The velocity and shaft torque can be combined to obtain the transient fan torque load T_F.

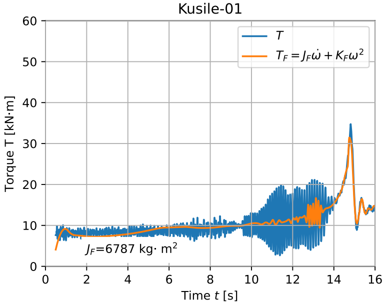
$$T_F = J_F\dot{\omega} + K_F\omega^2$$

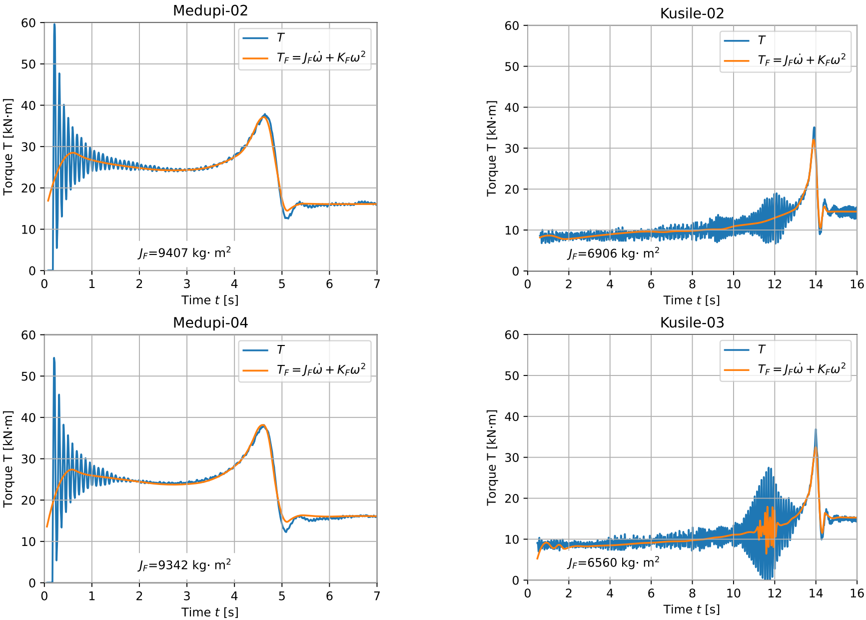
The aerodynamic load factor $K_F = \bar{T}/\bar{\omega}^2$ with $\bar{T}$ and $\bar{\omega}$ averages in the steady state region.

The fan inertia J_F is calculated with a least-squares optimization procedure in the start-up region

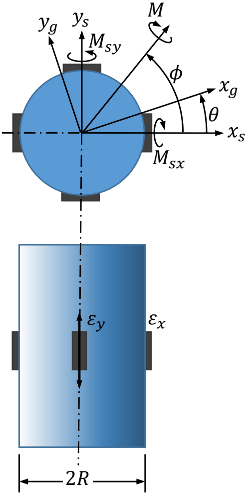
$$\epsilon(J_F) = \sum_i \left[T_i - \left(J_F\dot{\omega}_i + K_F\omega_i^2\right)\right]^2$$






Medupi-02
Torque T [kN·m]
Time t [s]
T
$T_F = J_F\dot{\omega} + K_F\omega^2$
J_F=9407 kg· m^2
Kusile-02
Torque T [kN·m]
Time t [s]
T
$T_F = J_F\dot{\omega} + K_F\omega^2$
J_F=6906 kg· m^2
Medupi-04
Torque T [kN·m]
Time t [s]
T
$T_F = J_F\dot{\omega} + K_F\omega^2$
J_F=9342 kg· m^2
Kusile-03
Torque T [kN·m]
Time t [s]
T
$T_F = J_F\dot{\omega} + K_F\omega^2$
J_F=6560 kg· m^2

Shaft bending



$$M_{sx} = K_M \cdot \varepsilon_y$$
$$M_{sy} = K_M \cdot \varepsilon_x$$

Full-bridge bending strain gauges are fitted symmetric in the axial direction of the shaft. For a strain ε along the direction of the gauge the moment-strain relationship is

$$M = \frac{1}{4}\pi E R^3 \cdot \varepsilon$$

with M Applied moment [N·m]

ε Strain [m/m]

$R = 89.25$ mm Shaft radius

$E = 207$ GPa Young's modules

The gauge constant is then

$$K_M = \frac{M}{\varepsilon} = \frac{1}{4}\pi E R^3 = 115.581 \, \frac{\text{N·m}}{\mu\text{m/m}}$$

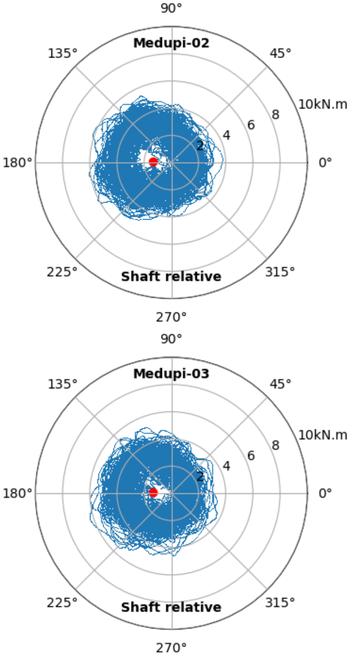
The bending moments are measured in the x- and y-direction. Total moment and direction relative to the shaft at time t

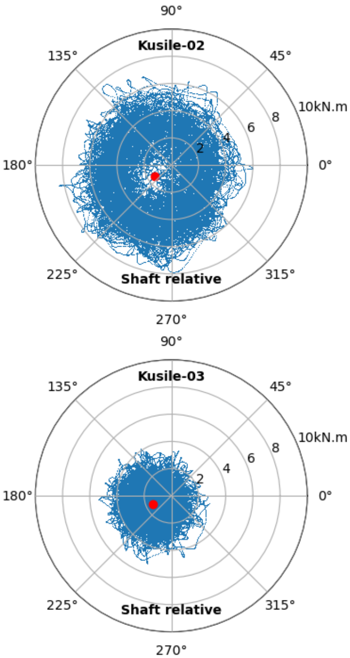
$$M = \sqrt{M_{sx}^2 + M_{sy}^2}, \qquad \phi = \tan^{-1}(M_{sy}/M_{sx})$$

The shaft rotation θ_i at the velocity signal peak times τ_i is

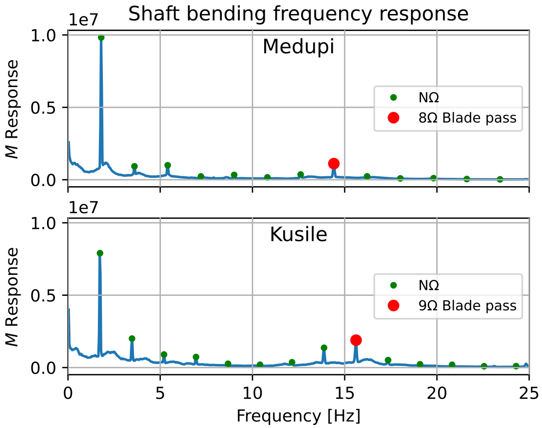
$$\theta_i = \theta_0 + 2\pi i/n$$

Constructed spline $(\tau_i, \theta_i) \rightarrow \mathcal{S}_\theta$ with $\theta(t)=\mathcal{S}_\theta(t)$


Medupi-02
Shaft relative
Medupi-02
Gearbox relative
Medupi-03
Shaft relative
Medupi-03
Gearbox relative
90°
45°
0°
315°
270°
225°
180°
135°
2
4
6
8
10kN.m


Kusile-02
Shaft relative
Kusile-02
Gearbox relative
Kusile-03
Shaft relative
Kusile-03
Gearbox relative
90°
45°
0°
315°
270°
225°
180°
135°
10kN.m
2
4
6
8

Shaft Bending



Find the average frequency response over a long time (3 hours in this instance) to smooth out noise

- FFT ($N_{\text{FFT}} = 2^{15}$, Han windowed)
- 50% overlap for successive FFT windows.
- Sample frequency $f_s = 1200$ Hz

Conclusions

Speed measurement:

- Low cost speed sensor was developed.
- Sub-rotation accuracy start-up angular velocity and acceleration.

Shaft torsion:

- Very large torque peaks during direct startup at Medupi.
- Low system torsional excitation at Medupi.
- Soft-starts can result in very large start-up torque peaks at Kusile.
- High system torsional excitation at blade pass frequency at Kusile.

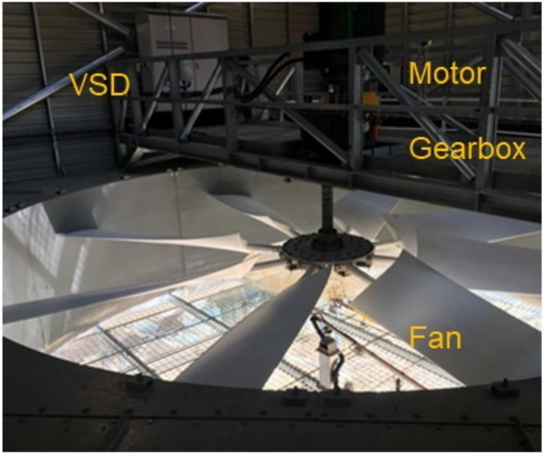
Shaft bending:

- Unbalanced loads relative to shaft detected.
- Large bending loads on bearings.

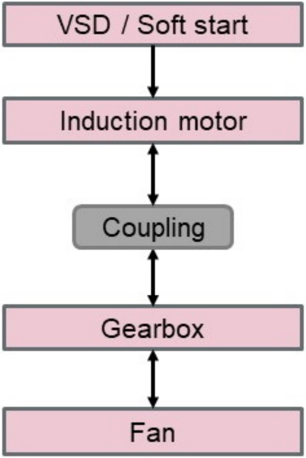
General:

- Measured data can be used to develop and verify system models.

System Dynamic Modelling

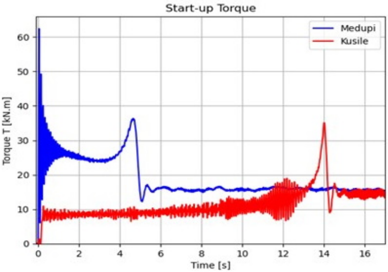


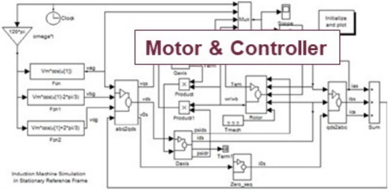
MinWaterCSP ACC test facility

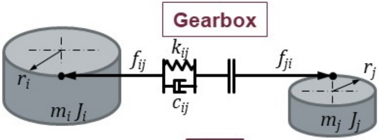


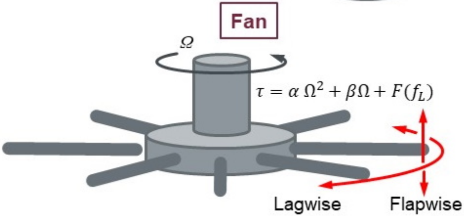
System Dynamic Modelling

- The objective is an integrated model for the torque loads through the mechanical system of an ACC.
- The main purpose of the model is to investigate and predict the start-up and steady state mechanical loads through out the system.









Thank you | Dankie | Enkosi