Liebherr D934 digital twin model description

DTL

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In this document we describe the Liebherr diesel engine D934 represented in the Digital Twin Library. The model is based on the main dynamical equation of the crank-shaft and doesn't take into account the internal combustion thermodynamic. Torque curve as well as consumption contour map is taken from supplier and implemented as lookup table.

1 Technical data

The following technical data has been taken into account during the modelization of the engine.

Rated Power	175 kW
at engine speed	$1600\,\mathrm{min}^{-1}$
Torque max	1250 N m
at engine speed	$1300\,\mathrm{min}^{-1}$
Engine speed	
low idle speed, standard	$600\,\mathrm{min}^{-1}$
maximum no load speed, max	$2140\,\mathrm{min}^{-1}$
nominal engine speed	$1900\,\mathrm{min}^{-1}$
Fuel consumption	
at rated power	196 g/kWh
at full load, min	192 g/kWh
at characteristic map best point	191 g/kWh

Table 1: Liebherr diesel engine D934 data.

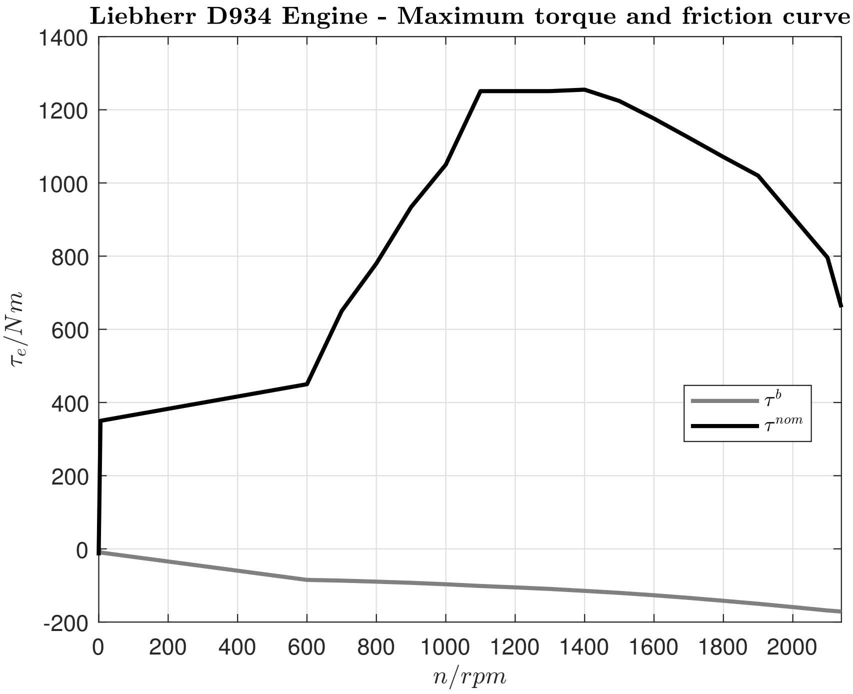

Figure 1: Liebherr diesel engine D934 - maximum torque and friction curve.

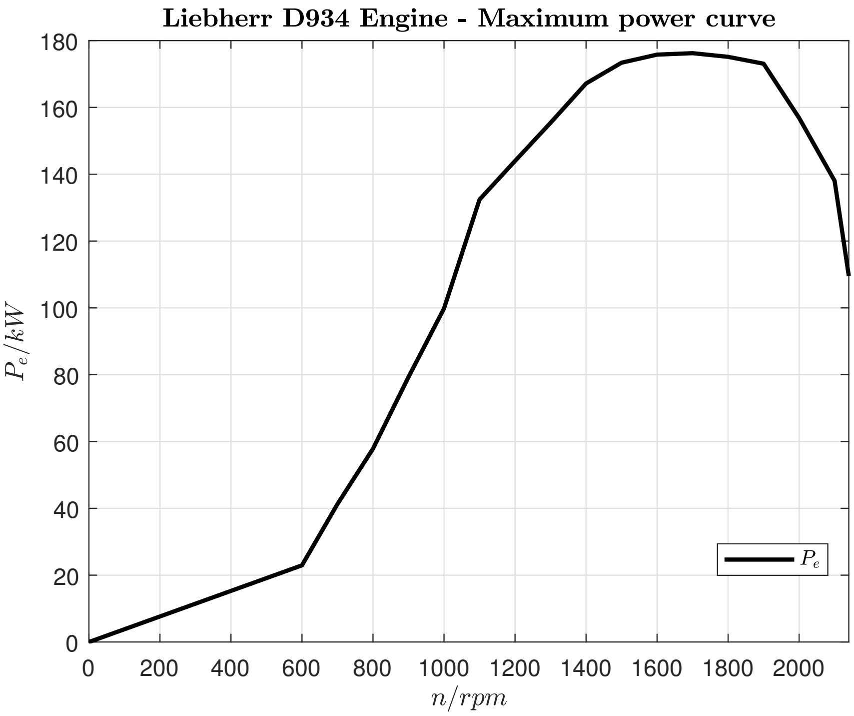

Figure 2: Liebherr diesel engine D934 - maximum available power at the crankshaft.

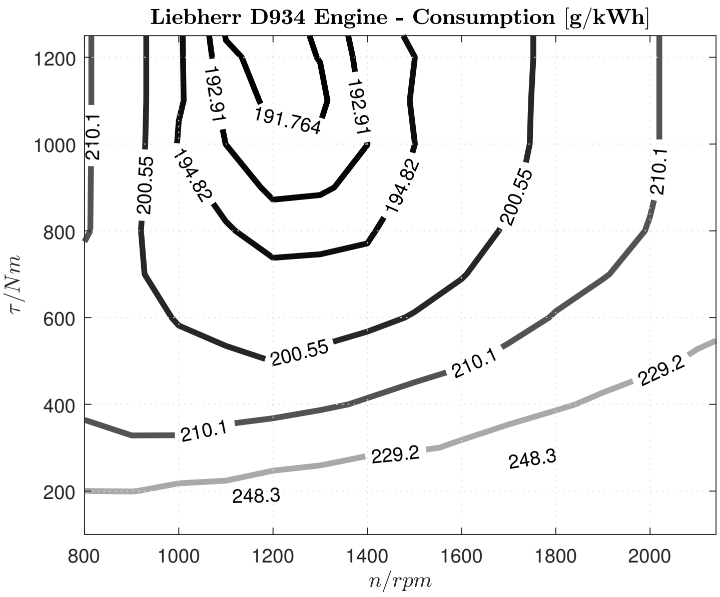

Figure 3: Liebherr diesel engine D934 - Consumption map in [g/kWh].

In the next figures the torque step responses at different rotor speed have been shown. Figure 4 shows the torque step response of the engine at rotor speed of $n = 1400\,\mathrm{min}^{-1}$

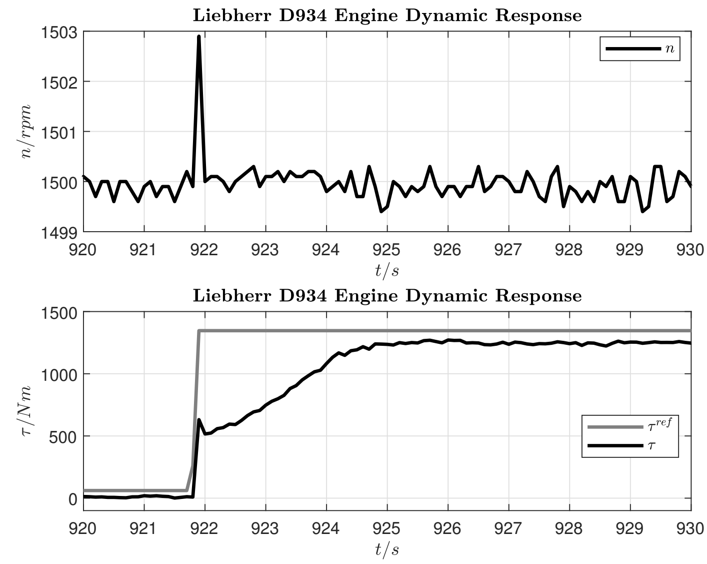

Figure 4: Liebherr diesel engine D934 - step response.

Figure 5 shows the torque step response of the engine at rotor speed of $n = 1800\,\mathrm{min}^{-1}$

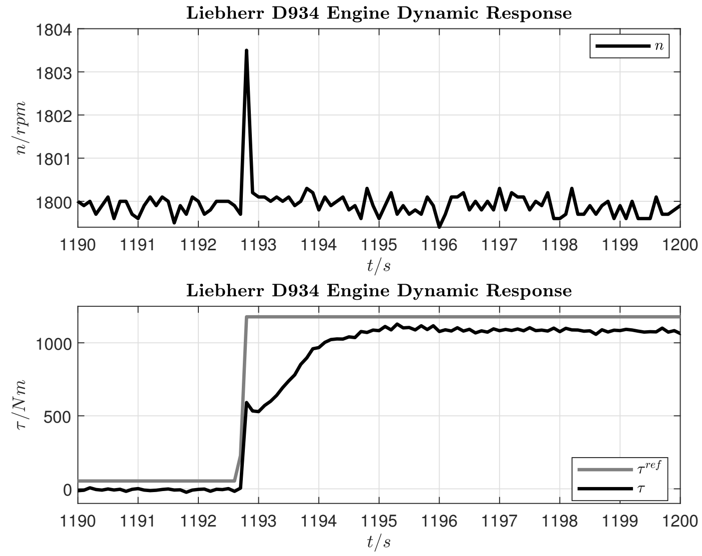

Figure 5: Liebherr diesel engine D934 - step response.

Figure 6 shows the torque step response of the engine at rotor speed of $n = 2100\,\mathrm{min}^{-1}$

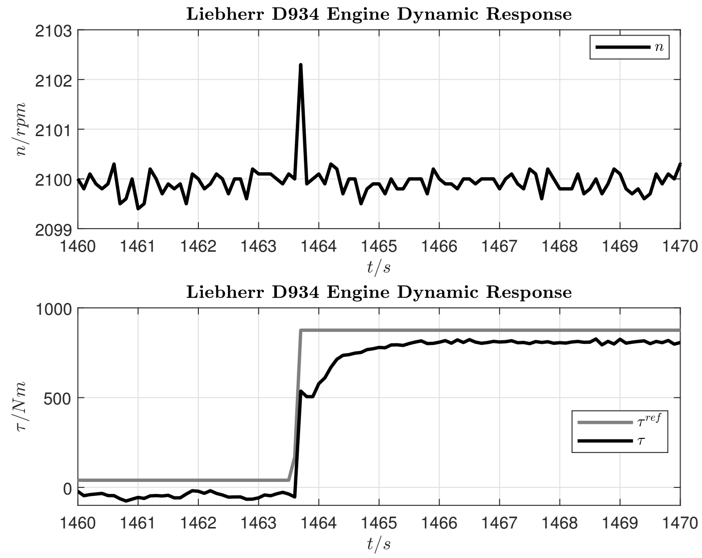

Figure 6: Liebherr diesel engine D934 - step response.

In the next section the equivalent mathematical model of the Liebherr D934 diesel engine will be proposed.

2 Equivalent mathematical model

In this section the description of the IC-engine is reported. The knowledge of the torque and power curve of the engine plays an important role in the performance of the engine anti-stall control.

In the following, we describe how the IC-engine has been modelized. We start to consider two curves:

- Torque curve: maximum torque available for a given rotor speed and maximum displacement of the throttle.
- Torque friction curve: torque generated by the friction for a given rotor speed. This friction is considered always present, for any value of the throttle. See also Figure 1

The mechanical model of the engine can be described as follows

$$J\frac{d\omega_e}{dt} = \theta_f(t)\tau^{nom}(\omega_e) + \tau^b(\omega_e) - \tau_{load} - |\tau_{ebs}| \tag{2.1}$$

where $\tau^{nom}(\omega_e)$, $\tau^b(\omega_e)$ are shown in Figure 1. $\theta_f(t)$ is the throttle which is generated by the external speed loop control as shown in Figure 7 and $J = 7.5\,\mathrm{kg\,m^{-2}}$.

The speed control is performed by a PI-controller and it adapts the throttle displacement in order to keep the request speed tracked.

An additional second order filter is taken into account in order to modelize additional dynamics.

The controller can be described as follows

$$\begin{cases} \tilde{\omega}_e(t) = \dfrac{1}{\omega_e^{\mathrm{nom}}}\Big(\omega_e^{\mathrm{ref}} - \omega_e(t)\Big) \\ \theta(t) = k_p\,\tilde{\omega}_e(t) + \theta^i(t) \\ \dfrac{d\theta^i}{dt}(t) = k_i\,\tilde{\omega}_e(t) \end{cases} \tag{2.2}$$

The control output θ is passed through a second order filter:

$$\theta_f(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}\theta(s) \tag{2.3}$$

where $\zeta = 1$ and $\omega_0 = 2\pi 25\,\mathrm{Hz}$.

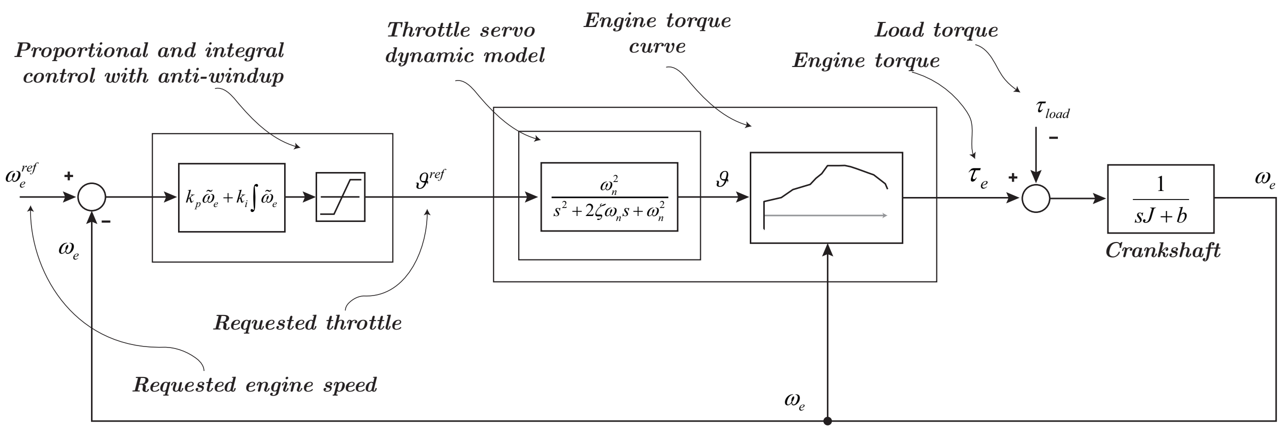

Figure 7: Engine model and control architecture.

3 Model parameters settings

Parameters setting consist of two parts

- Engine parameters
- Control parameters

Engine model parameters consist of the following data

- **Inertia**: This parameter sets the total inertia which is comprehensive of the crank-shaft and (if included) the wheel.

$$J \text{ in } \left[\mathrm{kg\,m^2}\right]$$

- $\boldsymbol{\omega_0}$: This parameter sets the initial engine rotation speed

$$\omega_0 \text{ in } \left[\mathrm{min^{-1}}\right]$$

Control parameters consist of the parameters which affect the PID speed control

- k_p This parameter sets the proportional gain of the PID control.
- k_i This parameter sets the integral gain of the PID control.
- k_d This parameter sets the derivative gain of the PID control (typically set to zero).

4 Model output variables

The output bus channel **ENGINE data** includes the following data output

- P_e: Engine power (power correlated to the consumption) $\left[\mathrm{kW}\right]$.
- ω_e: Engine speed $\left[\mathrm{min^{-1}}\right]$.
- τ_e: Engine torque $\left[\mathrm{N\,m}\right]$.
- fc^s: Specific fuel consumption $\left[\mathrm{g/kWh}\right]$.
- fc: Fuel consumption $\left[\mathrm{g}\right]$.
- ϑ: throttle in %.