

Control strategy of speed pulsations on hybrid powertrains

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Background and motivations

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- Robustness control.

Hybrid test bench

A study and tests has been carried out on the experimental bench of the University of Poitiers. Using Matlab simulink a test bench simulator is based on this hybrid platform.

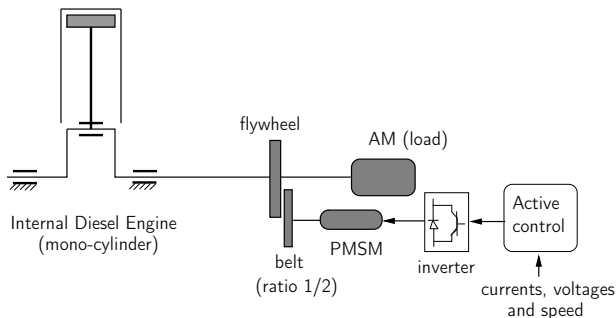


Fig. 1. Global scheme of the hybrid test bench

Hybrid test bench

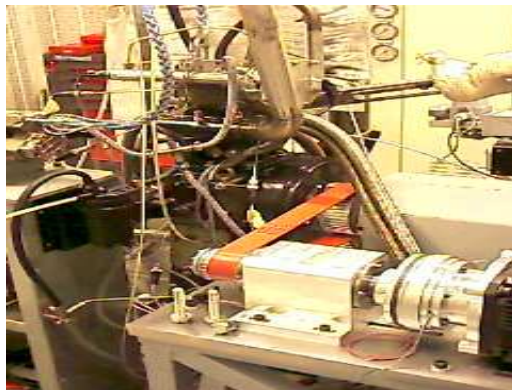
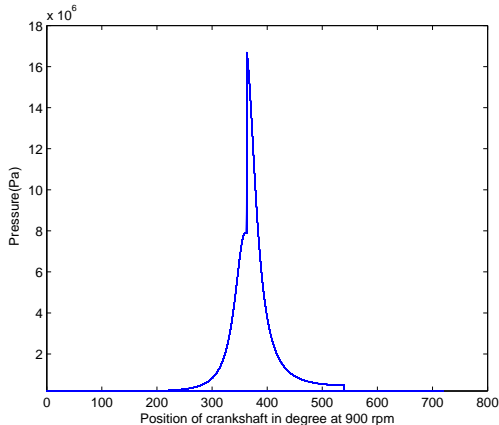


Fig. 2. The HEV powertrain part of the test bench

Internal diesel engine

The internal diesel engine is a 0.5l Renault mono-cylinder. At 900 rpm, the pressure in the cylinder is depicted on this figure.



Internal diesel engine

T_p and T_i are given by

$$\begin{aligned}
 T_p &= P_r(\theta) \left[r \cos(\theta) + l \sqrt{1 - \lambda_m^2 \sin^2(\theta)} \right] \tan(\varphi) \\
 T_i &= (m_a + m_p) \omega^2 r [\cos(\theta) + \lambda_m \cos(2\theta)], \\
 &\quad \left[r \cos(\theta) + l \sqrt{1 - \lambda_m^2 \sin^2(\theta)} \right] \tan(\varphi). \quad (1)
 \end{aligned}$$

where T_i is the torque generated by oscillating masses and connecting rods, T_p is the combustion torque generated by the pressure in the cylinder, $\sin(\varphi) = -\lambda_m \sin\theta$, $P_r(\theta)$ is the upward thrust on the piston. $\lambda_m = \frac{r}{l}$ where l is the length of the connecting rod and r is the rayon of the rod. m_a represents the mass of the rod and m_p the mass of the piston.

Permanent magnet synchronous machine

Using the d-q transformation, the permanent magnetic synchronous machine is described in the rotor reference frame as follows ,

$$\begin{aligned}\frac{di_d}{dt} &= -\frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega i_q + \frac{1}{L_d}v_d \\ \frac{di_q}{dt} &= -\frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega i_d + \frac{1}{L_q}v_q - \frac{\lambda}{L_q}p\omega,\end{aligned}\quad (2)$$

- v_d and v_q are the stator voltages,
- i_d and i_q are the armature currents,
- p is the number pole pairs,
- ω is the rotor electrical speed,
- R is the stator phase resistance,
- L_d and L_q are the stator reluctance,
- λ is the flux linkage per phase established by rotor permanent magnet.

Permanent magnet synchronous machine

The torque of the electric motor is given by:

$$T_m = \frac{3}{2}p [(L_d - L_q)i_d i_q + \lambda i_q] \quad (3)$$

The commonly used strategy is the constant torque-angle control: the d-axis reference current is made to be zero, and the electromagnetic torque is controlled by the q-axis current and its equation becomes,

$$T_m = \frac{3}{2}p\lambda i_q$$

T_m is the torque of the synchronous machine coupled to the internal combustion from the crankshaft.

Hybrid powertrains

The dynamics models of the mechanics of the hybrid powertrains can be represented in state-space form:

$$\begin{aligned}\dot{\theta} &= \omega \\ J\dot{\omega} &= (T_p + T_i) + T_m - T_l\end{aligned}\quad (4)$$

with J is the mass moment of inertia of the passive flywheel and the synchronous machine and T_l is the exogenous load torque. θ and ω are crankshaft position and speed respectively.

In the figure, the speed of the diesel engine (down) and electrical motor (up) are shown. The ratio is two between both speeds which is due to the reduction between the both shafts.

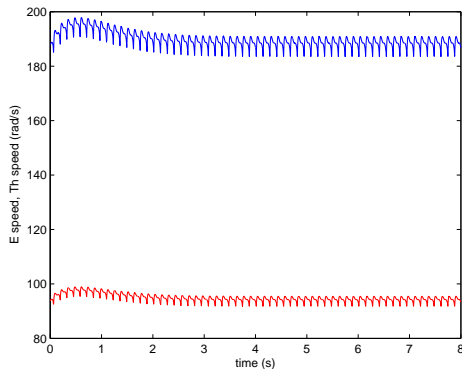


Fig. 4. Speed of internal combustion engine and electrical motor

Frequency analysis of the thermal and electrical speed.

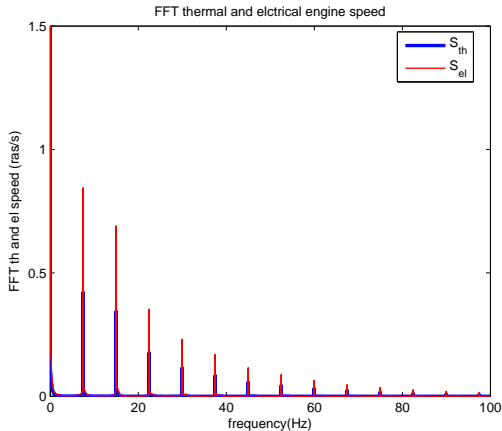


Fig. 5. FFT analysis of the thermal and electrical speed signal

Basic idea

Our idea consists to control instantaneous torque of the electrical motor in order to remove torque ripples of the diesel engine. It is the way to counteract motor torque ripple in hybrid vehicles.

Control strategy

- The control design is based on state space representation of the controlled system. The objectives assure the stability of the closed loop system and the performances, in order to cancelate the speed fluctuations to compensate the torque ripples.
- The analytic representation of Hilbert transformation assure the time-frequency analysis of the speed which frequencies components are time varying. It characterizes and chooses which harmonic of the spectrum is canceled.

Control strategy

The control loop

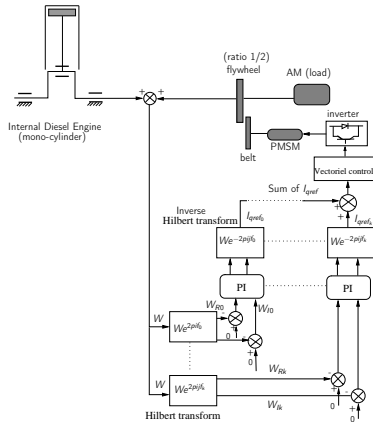


Fig. 6. Control loop

Control strategy

The part control loop

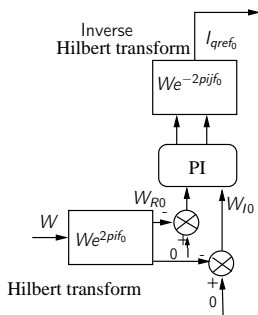


Fig. 7. Part of the Control loop

Model in Hilbert transformation

Let introduce $h(t)$, with the hilbert transform, the analytic signal at the frequency ω_0 of $H(t)$ as:

$$h(t) = H(t) e^{j\omega_0 t}$$

with a complex $X(t) = X_R(t) + jX_I(t) \in \mathbb{C}$

Therefore, the dynamics of the speed can be written as follow,

$$\begin{aligned} \dot{\theta} + j\omega\theta &= \omega \\ J(\dot{\omega} + j\omega_0\omega) &= (T_p + T_i) + \frac{3}{2}p\lambda i_q - T_l \end{aligned}$$

Model in Hilbert transformation

Let introduce $\omega(t) = \omega_R(t) + j\omega_I(t)$, $I_q(t) = I_{qR}(t) + jI_{qI}(t)$ and $T = (T_p + T_i) - T_I = (T_R + jT_I)$ then,

$$\dot{\theta} + J\omega\theta = \omega_R + j\omega_I \quad (5)$$

$$J(\dot{\omega} + j\omega_0(\omega_R + j\omega_I)) = (T_R + jT_I) + \frac{3}{2}p\lambda(I_{qR} + jI_{qI}). \quad (6)$$

The current loop of the synchronous motor can be modeled as a first order.

$$i_q(s) = \left(\frac{1}{1 + \tau_e s} \right) i_{qref}(s), \quad (7)$$

Model in Hilbert transformation

Then, the state space model is given by,

$$\begin{aligned}\dot{x} &= A(\omega_0)x + B_w w + B_u u \\ y &= C_y x + D_{yu} u,\end{aligned}\tag{8}$$

- $w^T = [T_R, T_I]$ is the vector of exogenous inputs (Torque perturbation in the Real and Imaginary axis),
- $x^T = [\omega_R, \omega_I, I_{qrefI}, I_{qrefR}]$ is the state vector,
- $u^T = [u_R, u_I]$ is the input vector,
- y is the vector of controlled outputs.

We have

$$A(\omega_0) = \begin{bmatrix} 0 & \omega_0 & \frac{3}{2J}p\lambda & 0 \\ -\omega_0 & 0 & 0 & \frac{3}{2J}p\lambda \\ 0 & 0 & -\frac{1}{\tau_e} & \omega_0 \\ 0 & 0 & -\omega_0 & -\frac{1}{\tau_e} \end{bmatrix},$$

$$B_u = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\tau_e} & 0 \\ 0 & \frac{1}{\tau_e} \end{bmatrix}, B_w = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, D_{yu} = 0$$

Robust PI controller

- The Hilbert transformation is used, the ripple torque disturbance is transformed into a constant disturbance.
- In order to reject perfectly, a constant disturbance, an integral action must be present in the controller.

Robust PI controller

- The synthesis of a multivariable PI controller achieving robust performance, or stabilization is based on H_∞ control. The controller is found with solving linear matrix inequality (LMI) for each harmonic.

Multivariable PI Controller,

$$u = F_1 y + \int_0^t F_2 y(\mu) d\mu, \quad (9)$$

F_1 and $F_2 \in R^{2 \times 2}$ are matrices to be designed.

Simulation results

The following gain matrices has been found for the harmonic at 15Hz,

$$F_{15} = \begin{bmatrix} -0.4366 & 0.0062 \\ -0.0062 & -0.4366 \end{bmatrix}; F_{2_{15}} = \begin{bmatrix} -0.3184 & -11.3700 \\ -11.3700 & 0.3184 \end{bmatrix}$$

The following gain matrices has been found for the harmonic at 22.5Hz,

$$F_{22.5} = \begin{bmatrix} -0.4544 & 0.0095 \\ -0.0095 & -0.4544 \end{bmatrix}; F_{2_{22.5}} = \begin{bmatrix} -0.9061 & -20.7248 \\ -20.7248 & 0.9061 \end{bmatrix}$$

Simulation results

The control law is applied to the simulation model.
This Figure presents the speed responses without active control from 0 to 7 s, and with active control after 7s.

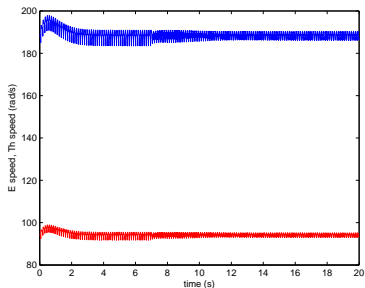


Fig. 8. Speed response with active controller

Frequency analysis of the thermal and electrical speed.

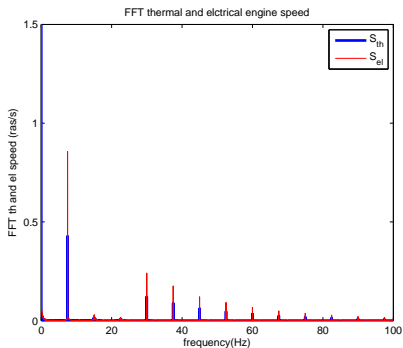


Fig. 9. FFT analysis of the speed signal with controllers

Conclusion

- A novel control strategy in order to reject torque ripples on hybrid powertrains is presented.

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- A LMI framework is used to synthesize the controller.
- Simulation results show the interest of this approach.
- Remove torque ripples on hybrid powetrains using super-capacitors.

Thanks for your attention!