Torque harmonic reduction in hybrid vehicles

M. Njeh, S. Cauet, P. Coirault and P. Martin

Abstract—In this paper, the authors propose a novel control strategy of torque ripple reduction in hybrid vehicles. The Internal Combustion Engine (ICE) ripples are reduced by an actuator and a Permanent Magnet Synchronous Machine (PMSM). This electric motor is mounted on the crankshaft in order to generate a torque sequence opposing the ripples. The control strategy is based on a static output feedback synthesis. The problem is reformulated in the time domain with regard to the main order of the fluctuations. An hybrid propulsion complete modeling is achieved from an experimental benchmark. The model is performed at low speed (900rpm). In fact, at this speed, the ripple is very restrictive. Simulation results highlight the control approach interest.

I. INTRODUCTION

The use of the Hybrid Electric Vehicle (HEV) is a way to reduce fuel consumption in transportation and the fuel dependence of this sector. Thus, it has become the most available technology and a great concern of the researchers in this field [1], [2], [3]. It guarantees high fuel economy, emissions reduction and ensures good performance such as increasing power or reducing vibration. In this advanced technology vehicle, at least two independent engines are used, usually a conventional internal combustion engine and an electric motor, that can be coupled in different ways referred as hybrid architectures. The most common architecture are parallel and series hybrid. Knowing that among the combustion engines, the Diesel units offer a better efficiency than the spark ignited ones, some car manufacturers like Daimler Chrysler and General Motors have already showed interest for Diesel hybrids. Because the Diesel engine creates much more vibrations than the gas engine, controlling its torque ripple would be appreciated.

In conventional internal combustion engine, the periodic fuel combustion in cylinders and the oscillating masses result in pulsing engine torque which affects the powertrain life cycle, causes increased noises, vibration and reduces the drivers comfort [4]. These limitations require an appropriate study to control engine torque which is one of the most important performance variables of an internal combustion engine. Usually, the mean value of the instantaneous torque over an engine cycle is controlled and the instantaneous torque waveform produced by the cylinders is imposed. Hence, only passive solutions are implemented to attenuate the torque pulsations as, for example, the flywheel.

HEV applications require high performance control of electric motor which can be used to control the instantaneous torque produced during combustion. Consequently, it can reduce undesirable effects. Some control strategies have been proposed. One possible application of the instantaneous torque control is the implementation of a virtual flywheel [5]. The impact is to reduce the flywheel mass or to control torsional vibration affecting the driveline. Previous experimental studies use observers to estimate the instantaneous torque in order to generate an instruction, which cancels the oscillating torque [6]. Moreover, the patent of Lorenz and Davis [7] proposes also, a virtual flywheel controlled by an observer, but it does not specify the type of engine used. Others researches have shown that open loop control of the electric motor reduces the engine speed oscillations [8]. In order to improve this control, an adaptive close loop control is needed. Simulations show that a harmonic activation neural network can be used to absorb the torque pulsation when using an AC machine [9] and a starter-generator [10]. The neural network gives interesting results, but it is controlled as a black box. There is no physical meanings and it is difficult to make the adaptation of the parameters. Also, simulations show that a learning control provides adequate active damping of engine crankshaft ripple and high robustness with respect to system parameter variations, especially flywheel inertia [11]. However, the actuator dynamics effects and sensor noise on learning control performance need to be evaluated. In addition, filtering technique is used to control the torque pulsation of the combustion engine using a band pass-filter to keep only a harmonic oscillation which can be canceled with electric motor [12], [13], [14].

In addition, the harmonic control is very well adapted for such active control problem of vibration [15] because it provides a disturbance narrow-band filtering which reduces the noise effects. Moreover, it was proved that the harmonic controller is a special case of time-frequency controllers adapted to reject time-varying tonal disturbances [16].

Hence, this paper proposes a way to control the torque created by the combustion engine of a parallel hybrid powertrains by developing an efficient controller using an estimation in real time by a harmonic decomposition of the ICE speed signal. This control is not based on harmonic compensation. The controller design is transformed into the synthesis of an output static control feedback problem. The problem of computing stabilizing static output feedbacks with constrained order on LTI (linear time-invariant) systems in terms of matrix inequalities is difficult to solve. In fact, a solution can be determined by a set of bilinear matrix inequalities (BMI). There are two techniques: the iterative algorithms and the elimination of variable products by using the matrix separation lemma. The second method has been chosen. In certain cases, this method transforms the initial
BMI into a set of linear matrix inequalities (LMI), which can be solved numerically [17], [18], [19], [20].

The paper is organized as follows. The next section presents the experimental hybrid bench of the University of Poitiers and the Simulink simulator, which is based on its hybrid powertrain. Models are representative of the hybrid test-bench. Section 3 presents the frequency analysis and synthesis of the engine speed and the control strategy. Results of simulation are presented in section 4.

II. HYBRID ELECTRIC MODEL

Test bench is an important tool for HEV control strategies research. That is why a study has been carried out on the experimental bench of the University of Poitiers. Using Simulink-Matlab, a test bench simulator has been developed. This simulator is based on the hybrid platform through a complete modeling, in order to design the control laws before their real implementation.

In order to develop and to optimize the parallel HEV control strategy, the test bench can evaluate and calibrate the parallel HEV powertrain control system and improves control algorithm. Also it conducts experiments of individual components like the engine, motor and others components such as the flywheel, the EGR and the combustion air circuit to provide the optimization of parameters matching and control strategies of the parallel HEV.

The experimental bench is depicted in Figure 2. A non-salient pole machine with air-gap permanent magnets has been chosen. In fact, the field-weakening range is not so wide and the partial-load efficiency is higher than known from induction motor. The PMSM performs high engine dynamics (15kW, Parvex Servo Motor HV 930 EL). It is coupled via a belt (Binder Magnetic belt AT10 GEN III, Pmax = 70kW) to the internal combustion engine through an electromagnetic clutch. There is a 1/2 ratio between each ICE and PMSM shafts. The load machine is a three-phase asynchronous motor (AM) of 47 kW. The AM motor speed controller dynamics are very low compared to the variations generated by the ICE. This machine able to deliver a load torque \( T_l \) on the crankshaft and can provide a road map. The thermal engine will be detailed in the following part.

In addition, a control system is needed to supply the control signals (e.g. electric motor control with the drive) and to acquire the measurement data (e.g. speed and torque signals of the shaft). It is done by the dSPACE rapid prototyping platform (dSPACE 1103) combined with a high performance PC, user friendly interface such as ControlDesk, a dSPACE software control platform, and Matlab-Simulink to run the real time operating system and to perform the online parameter fitting and monitoring. The speed and position internal combustion engine crankshaft angle is measured with a 2048pt/rd rotary encoder attached to the crankshaft (Incremental coder, series DHM9100C). The PMSM speed and position is also measured by a resolver.

In the following section, the each part model of the hybrid test bench is developed.

A. Internal Diesel Engine

The internal diesel engine is a 0.5 l mono-cylinder of Renault International Company. The internal combustion engine ripple is very restrictive at low speed. Many vibrations are undesired at low frequencies. So, at idle, the motor is around 900 rpm. The dynamic model of the ICE mechanics can be represented in state-space form as follows

\[
\begin{align*}
\dot{\theta}_{th} &= \omega_{th} \\
J_l \dot{\omega}_{th} &= k(\theta_{el} - \theta_{th}) + c(e\omega_{el} - \omega_{th}) + (T_p + T_l) - T_i
\end{align*}
\]

where \( J_l \) is the inertia mass moment of the passive flywheel, \( T_i \) is the torque generated by oscillating masses and connecting rod, \( T_p \) is the combustion torque generated by the pressure in the cylinder, \( T_i \) is the exogenous load torque, \( k \) is the stiffness of the belt, \( c \) is the damping coefficient of the belt, \( n \) is the ratio between ICE and PMSM axes, \( \theta_{th} \) and \( \omega_{th} \) are crankshaft position and speed respectively. \( \theta_{el} \) and \( \omega_{el} \) are rotor position and speed respectively.

The mathematical models of \( T_p \) and \( T_i \) are given by

\[
T_p = P_r(\theta_{th}) \left[ r \cos(\theta_{th}) + l \sqrt{1 - \lambda_m^2 \sin^2(\theta_{th})} \right] \tan(\varphi),
\]

\[
T_i = (m_a + m_p)\omega^2 r \left[ \cos(\theta_{th}) + \lambda_m \cos(2\theta_{th}) \right] \left[ r \cos(\theta_{th}) + l \sqrt{1 - \lambda_m^2 \sin^2(\theta_{th})} \right] \tan(\varphi),
\]

with

\[
\tan(\varphi) = \frac{\lambda_m \sin(\theta_{th})}{\sqrt{1 - \lambda_m^2 \sin^2(\theta_{th})}}
\]
where $\sin(\phi) = -\lambda_m \sin(\theta_{th})$, $P_r(\theta_{th})$ is the upward thrust on the piston. $\lambda_m = \frac{l}{r}$ where $l$ and $r$ are the connecting-rod length and the crank radius. $m_a$ and $m_p$ represent the mass of the connecting rod and the piston respectively.

The parameters of the internal combustion engine are:
- Maximum torque: $80 \text{ Nm}$ to $2000 \text{ rpm}$,
- Maximum instantaneous torque: $2000 \text{ Nm}$,
- Speed operation range: $200$ to $4500 \text{rpm}$.

Table I presents the values used for the parameters of the ICE.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the rod</td>
<td>0.335 Kg</td>
</tr>
<tr>
<td>Mass of the piston</td>
<td>0.840 Kg</td>
</tr>
<tr>
<td>Rayon of the rod</td>
<td>$49 \times 10^{-3}$ m</td>
</tr>
<tr>
<td>Length of the rod</td>
<td>0.144 m</td>
</tr>
<tr>
<td>Diameter of the piston</td>
<td>0.0825 m</td>
</tr>
<tr>
<td>Rod center of mass</td>
<td>0.093 m</td>
</tr>
<tr>
<td>Mass of the crankshaft</td>
<td>1 Kg</td>
</tr>
<tr>
<td>Inertia of the passive flywheel</td>
<td>2.82 Kg m²</td>
</tr>
</tbody>
</table>

TABLE I
VALUES USED FOR THE SIMULATION

In Figure 3, the speed of the diesel engine (down) and electric machine (up) are shown. The ratio is two between both speeds, which is due to the reduction between both shafts.

A way to control the torque ripples created by the ICE is to use the electric motor as a torque controller source. The ICE is connected to the electric motor in order to ensure a more constant speed signal. In this case, it achieves an active control of the torque ripples.

Frequency analysis of the diesel speed signal, presented in Figure 4, shows the ripple phenomenon resulted in the harmonics, which are due to the explosion phenomenon in the engine combustion chamber. The different harmonics are products of the $7.5Hz$ frequency which corresponds to the fundamental of $900$ rpm.

So, the idea is to control instantaneous torque of the electric motor in order to reduce ripple speed of the diesel engine. It is the way to counteract motor torque ripple in hybrid vehicles. However, the torque control of the synchronous motor requires a modelization. It is the objective of the following part.

B. Permanent magnet synchronous machine

The mathematical model of the PMSM in a synchronous rotating d-q reference frame can be given by [21] 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 the equation torque of the electric motor becomes

$$T_{em} = \frac{3}{2} p \lambda_i q,$$

where $i_q$ is the q-axis current; $T_{em}$ is the electromagnetic torque; $p$ is the number of pole pairs and $\lambda$ is the flux linkage per phase established by rotor permanent magnets.

The dynamic model of the mechanics of the electric machine used in the hybrid powertrain can be represented in state-space form as follows:

$$\dot{\theta}_{el} = \omega_{el},$$
$$J_2 \dot{\omega}_{el} = k_i (\theta_{th} - \theta_{el}) + c (\omega_{th} - \omega_{el}) + T_{em},$$

where $J_2$ is the inertia mass moment of the synchronous machine.

Table II presents the parameters values of the PMSM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>$15$ kW</td>
</tr>
<tr>
<td>Rated torque</td>
<td>$64$ Nm</td>
</tr>
<tr>
<td>Number of pole pair</td>
<td>$5$</td>
</tr>
<tr>
<td>Torque Coefficient</td>
<td>$0.214$ V</td>
</tr>
<tr>
<td>Inductance in axis q</td>
<td>$10.9$ mH</td>
</tr>
<tr>
<td>Resistance of a phase</td>
<td>$0.464$ Ω</td>
</tr>
<tr>
<td>Stiffness of the belt</td>
<td>$10000$ N·m/m</td>
</tr>
<tr>
<td>Damping coefficient of the belt</td>
<td>$18$ N·s/m</td>
</tr>
</tbody>
</table>

TABLE II
VALUES USED FOR THE SIMULATION

III. CONTROL STRATEGY

In hybrid powertrains, the electric motor can be used to control the instantaneous torque produced by the thermal engine in order to remove ripple speed through the generation of a reverse torque. The originality of the proposed approach is to consider one PI controller which will act on all harmonics in order to track current reference $i_{qref}$. The control design is based on a state space representation of the controlled system. The objective is
to ensure the stability of the closed loop system and the performance, in order to attenuate the speed fluctuations to compensate the torque ripples.

The control loop has been depicted in Figure 5. There is a control loop for all harmonics of the speed signal to reduce significantly their amplitudes.

![Control Loop Diagram](image)

**Fig. 5. Control loop**

### A. Model in state space form

The state space model is given by

\[
\dot{x} = Ax + B_w w + B_u u, \quad y = C_p x + D_{yu} u, \tag{5}
\]

where \( x^T = [\theta_{th}, \omega_{th}, \theta_{el}, \omega_{el}] \in \mathbb{R}^n \) is the state vector, \( u = i_{qref} \in \mathbb{R}^n_u \) is the input vector, \( y \in \mathbb{R}^p \) is the controlled vector outputs and \( w = C_p + C_t - C_e \in \mathbb{R}^n_w \) is the exogenous inputs vector (Torque perturbation ). We have

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & -1 \\
\frac{1}{2} & 0 & 0 & 1 \\
\frac{1}{2} & 0 & 0 & 1 \\
\end{bmatrix}, \quad B_u = \begin{bmatrix}
0 \\
0 \\
1 \\
1 \\
\end{bmatrix}, \quad B_w = \begin{bmatrix}
0 \\
1 \\
0 \\
0 \\
\end{bmatrix}, \quad C_p = \begin{bmatrix}
0 & 0 & 1 \\
0 & 0 & 0 \end{bmatrix}, \quad D_{yu} = 0_{n_x n_u}.
\]

Assume that the current controller of the synchronous motor can be modeled as a first order,

\[
i_q(s) = \left(\frac{1}{1 + \tau_e s}\right)i_{qref}(s), \quad \tau_e \text{ is the first order constant of the current control loop. In our case we choose } \frac{1}{\tau_e} = 600 \text{ Hz}. \tag{6}
\]

For this control and from the measured signals, it is necessary to estimate in real time the speed signal of the ICE from which it is possible to reconstruct the desired reference signal. It ensures the reduction or elimination of the unwanted harmonics according to the coefficients choice of each harmonic of the estimated signal during the reconstruction step of the reference signal. Thus, after estimation, some harmonics are attenuated or canceled. Then a reference trajectory can be rebuilt by a reconstruction step.

Assume that for constant or slow variations of speed, we have:

\[
\omega_{th}(t) = \tilde{\omega}_{th}(t) + \hat{\omega}_{th}(t) \tag{7}
\]

where \( \tilde{\omega}_{th} \) is the mean value of \( \omega_{th} \) and \( \hat{\omega}_{th} \) stands for the speed variations around the mean value.

With this assumption, a model of the speed can be expressed as:

\[
\omega_{th}(t) = \sum_{i=0}^{N} a_i(t) e^{j\theta_{th}(t)} \tag{8}
\]

with \( a_i(t) \) a complex coefficient \( a_i(t) = a_{Ri}(t) + j a_{Ii}(t) \in \mathbb{C} \) and \( N = 8 \) is the number of harmonics used to reconstruct the speed signal in our case.

Therefore, the model can be written as follows,

\[
\omega_{th}(t) = \sum_{i=0}^{N=8} a_{Ri}(t)\cos(i\theta_{th}(t)) - a_{Ii}(t)\sin(i\theta_{th}(t)) + j (a_{Ri}(t)\sin(i\theta_{th}(t)) + a_{Ii}(t)\cos(i\theta_{th}(t))) \tag{9}
\]

The signal \( \omega_{th}(t) \) is real, then (9) leads to

\[
\begin{cases}
\omega_{th}(t) = \sum_{i=0}^{N=8} a_{Ri}(t)\cos(i\theta_{th}(t)) - a_{Ii}(t)\sin(i\theta_{th}(t)) \\
0 = a_{Ri}(t)\sin(i\theta_{th}(t)) + a_{Ii}(t)\cos(i\theta_{th}(t))
\end{cases}
\]

Let

\[
\varphi(t) = \begin{bmatrix}
1 & 0 & \cos(\theta_{th}(t)) & -\sin(\theta_{th}(t)) & \cdots \\
0 & 1 & \sin(\theta_{th}(t)) & \cos(\theta_{th}(t)) & \cdots \\
\cos(N\theta_{th}(t)) & -\sin(N\theta_{th}(t)) & \cos(N\theta_{th}(t)) & \cdots \\
\sin(N\theta_{th}(t)) & \cos(N\theta_{th}(t)) & \cdots 
\end{bmatrix}, \tag{10}
\]

and \( y(t) = [\omega_{th}(t) \quad 0]^T \), the solution of the least squares algorithm, for the parameters \( a_{Ri} \) and \( a_{Ii} \), is given by

\[
\hat{a}_i = \left(\sum_t \varphi^T(t) \varphi(t)\right)^{-1} \sum_t \varphi^T(t)y(t). \tag{12}
\]

Point out the effectiveness of the estimation approach, frequency analysis of the engine speed signal, presented in Figure 6, shows the comparison of the measured signal with the estimate of the first 8 harmonics and the continuous component on this signal.

In practice, to take into account the slow variations of the speed compare to the system dynamics, parameters \( \hat{a}_i \) are estimated thanks a recurrence least squares with a forgetting factor. Note that in this estimation approach, there is no need to use a low-pass band filter. Then the harmonic reconstruction of engine speed is allowed in a sufficiently short time to ensure the control loop stability despite of slow speed variations.

### B. Design PI controller

In this part, the design problem of PI controller under \( H_{\infty} \) performance specification is investigated. The controller is found by solving linear matrix inequalities

Consider the system (5) with the following PI,

\[
u = F_1 y + F_2 \int_0^t y(\mu)d\mu, \tag{13}\]
The matrices $F_1$ and $F_2 \in \mathbb{R}^{n_u \times n_y}$ are matrices to be designed.

Let $z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} x \\ \int_0^x y(\mu) d\mu \end{bmatrix}$.

Combining equations (5), (13) and the definition of $z$, the system can be represented in the augmented form as,

$$
\dot{z} = \bar{A}(\omega_0)z + \bar{B}_uw + \bar{B}_uw.
$$

The matrices $\bar{A}$, $\bar{B}_u$ and $\bar{B}_w$ are defined as follows,

$$
\bar{A} = \begin{pmatrix} A & 0 \\ C & 0 \end{pmatrix}, \quad \bar{B}_u = \begin{pmatrix} B_u \end{pmatrix}, \quad \bar{B}_w = \begin{pmatrix} B_w \end{pmatrix}
$$

Let $\bar{y} = \begin{bmatrix} \bar{y}_1 \\ \bar{y}_2 \end{bmatrix}$ with,

$$
\begin{align*}
\bar{y}_1 &= \begin{pmatrix} C & 0 \end{pmatrix} z \\
\bar{y}_2 &= \begin{pmatrix} 0 & I \end{pmatrix} z.
\end{align*}
$$

In this case, we have,

$$
\begin{align*}
u &= F_1\bar{y}_1 + F_2\bar{y}_2 = \begin{pmatrix} F_1 & F_2 \end{pmatrix} \bar{y} = \bar{F}\bar{y}.
\end{align*}
$$

Therefore, the problem of PI controller design is transformed into that of a static output feedback controller design for the system,

$$
\begin{align*}
\dot{z} &= \bar{A}(\omega_0)z + \bar{B}_uw + \bar{B}_wu \\
\bar{y} &= \bar{C}z \\
u &= \bar{F}\bar{y},
\end{align*}
$$

where,

$$
\bar{C} = \begin{pmatrix} C & 0 \\ 0 & I \end{pmatrix}.
$$

The static output feedback $H_\infty$ control problem is to find a controller $\bar{F}$ of the form (19) such that the closed loop transfer function $T_{wy}$ from $w$ to $y$ is stable when minimizing

$$
\|T_{wy}\|_\infty < \gamma,
$$

where $\gamma > 0$ and $\|\|_\infty$ denotes $H_\infty$ norm of system transfer matrix.

Also, a stabilizing controller providing such a $H_\infty$ norm, should lead the closed loop transfer function to satisfy a necessary and sufficient condition which is given by the following lemma (known as the Bounded Real Lemma)

**Lemma**: The $H_\infty$ norm of the closed loop transfer function is strictly lower than $\gamma$ if and only if there exists a strictly positive definite matrix $P$ such that

$$
\begin{pmatrix} PA_f + A_f^TP & PB_f & \bar{C}^T \\ \bar{B}_w^TP & -\gamma I & 0 \\ \bar{C} & 0 & -\gamma I \end{pmatrix} < 0
$$

with $A_f = \bar{A} + \bar{B}_u\bar{F}\bar{C}$, $B_f = \bar{B}_w$.

**Theorem**: Consider the system defined by (5), the closed loop system (19) is stable if the following conditions are satisfied,

1) The control vector $u$ is chosen to be $u = F_1\bar{y}_1 + F_2\bar{y}_2 = \bar{F}\bar{y}$.

2) Minimize $\gamma > 0$ over all variables of the following LMI $P = P^T > 0$

$$
\begin{pmatrix}
A_0P + P A_0^T & \bar{B}_w & P \bar{C}^T \\
\bar{B}_w^T P & -\gamma I & 0 \\
CP & 0 & -\gamma I
\end{pmatrix} < 0,
$$

where $A_0 = \bar{A} + \bar{B}_u\bar{F}_0$; $\bar{F}_0$: state feedback gain which stabilizes the system.

3) With $\bar{F}_0$, $P$ and $\gamma$, find $\bar{F}$ solution of the following LMI

$$
\begin{pmatrix}
0 & 0 & \bar{C}^T & P & 0 \\
0 & -\gamma I & 0 & 0 & 0 \\
P & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

$$
+ \text{Sym} \left\{ \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} \begin{pmatrix} A_0 & \bar{B}_w & 0 & -I & 0 \end{pmatrix} \right\}
$$

$$
+ \text{Sym} \left\{ \begin{pmatrix} f_1\bar{B}_w \\ f_2\bar{B}_w \\ f_3\bar{B}_w \\ f_4\bar{B}_w \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 & I \end{pmatrix} \right\}
$$

$$
+ \text{Sym} \left\{ \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} L\bar{C} - G\bar{F}_0 & 0 & 0 & -G \end{pmatrix} \right\}
$$

$< 0$

where $f_1, f_2, f_3$ and $f_4$ are non null matrices and matrices $G$ and $L$ are such that $\bar{F} = G^{-1}L$.

The proof of this theorem can be found in [22]. It is derived from lemmas found in [19].

**IV. Simulations Results**

In the following section, the simulation results of the control law described in the previous section are presented.
in order to improve the efficiency of the controller in counteracting periodic load disturbances.

The control law is applied on a test bench simulator. The diesel engine speed $\omega_{th}$ is around 900rpm (94.24 rad/s). The order $n_u \times n_y$ is considered for the design of the controllers.

The following parameters of PI controller has been found for the control loop in order to reduce the speed fluctuations.

$$F_1 = 6.0915,$$

$$F_2 = 13.5750.$$  

with $\gamma = 0.0462$

From the comparison of the frequency analysis of the thermal engine speed signal with and without active control, it is possible to note that there is a remarkable reduction of the harmonics amplitude in the application of the control loop as seen in Figure 7.

![FFT of the ICE speed](image)

**Fig. 7.** FFT of the ICE speed with controller( solid lines), FFT of ICE speed without controller(point marker).

This control loop is very useful to attenuate vibration on hybrid vehicle. In fact, only torque harmonics are generated and their mean values are around zero. This kind of control can be improved when the speed of the engine varies. One way is to use adaptive control or LPV control.

**V. CONCLUSION**

In this paper, we present a new control strategy of torque ripple reduction on hybrid vehicle. A brushless synchronous AC machine is used to compensate the torque ripple of the ICE. It has also been indicated that it is possible to do safe power with an oscillating torque without drawback on the mean torque. In fact the active anti-torque has an average value of zero according to the shaft angle. The control law is based on a state-output feedback controller, which is well suited for electrical drive. A LMI framework is used to synthesize the controller. Disabling the torque ripple control can allows quicker speed transients of the drivetrain over the traditional flywheel without compromising comfort. An extreme cases, it should be possible to alleviate the torque ripple totally, as a flywheel with an infinite mass. Simulation results show the interest of this approach. Further experiments are intended and it will be interesting to see if the control of torque ripple has an effect on the combustion process of the engine as well.

**REFERENCES**


