Torsional Oscillations Control of Integrated Motor-Transmission System Over Controller Area Network

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ABSTRACT Integrated motor-transmission (IMT) system is prone to suffer from torsional oscillations due to its fast dynamic behavior and weak damping characteristics. Meanwhile, signal communication between sensors, controllers and actuators via controller area network (CAN) that introduces time-varying delays, could also stimulate torsional oscillations in IMT system. Thus, this paper is intended to develop a robust controller to suppress these oscillations for IMT system during vehicle speed tracking. Considering the coupling effects of CAN-induced time-varying delays and event-driven manner of the controller nodes, as well as possible sampling period change, a delay-free discrete time model is built for IMT system by using polytopic inclusion approach and system augmentation technique. Based on this model, an energy-to-peak performance based robust controller is then developed for IMT system over CAN. It can achieve stable as well as good torsional oscillations suppression performance in spite of CAN-induced time-varying delays, sampling period change and also measurement noises. Finally, with a detailed CAN model developed by using SimEvent, conventional proportional-integral (PI) controller and energy-to-peak controller that designed with fixed sampling period are utilized in the comparative tests to show the effectiveness as well as performance of proposed torsional oscillations controller.

INDEX TERMS Torsional oscillations, robust energy-to-peak control, polytopic inclusion approach, controller area network, integrated motor-transmission.

I. INTRODUCTION

Powertrain electrification is a consistent tendency in recent years for ground vehicles [1]–[3]. It not only brings great significance in emission reduction, but also opens a wide range of opportunities to further improve vehicle dynamic control performance [4], [5]. Integrated motor-transmission (IMT) system is emerging as one promising solution for electrified powertrain systems [6], [7]. Compared with electric driving system with single ratio reducer, the IMT system can better balance the powertrain efficiency and vehicle dynamical performance by using gear shifting [8], [9]. Meanwhile, compact structure design of IMT can further help reduce the powertrain efficiency loss that caused by gear transmission system. However, it also increases the possibility of torsional oscillations in the powertrain system as the motor and gearbox are directly connected without damping components [10]. In order to suppress the torsional oscillations in electrified powertrain system, plenty of methods have been carried out, which generally can be classified into passive and active ones. In the passive approaches, increasing in inertia of driving motor can be one effective way to reduce the resonance [11], [12]. However, it’s not cost-effective in engineering practice.

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demonstrates more superiority in cost, convenience and flexibility [16], [17]. For the fully electrified powertrain system, shaft flexibility and gear backlash are generally considered as the principal causes of torsional oscillations [18], [19]. Amann et al [20] presented a nonlinear gear torque observer based damping controller for electrically driven vehicles, in which elasticity of the shaft and backlash in the gears are all considered. Lv et al [21] proposed a mode-switching based active controller for electrified powertrain system during regenerative braking, which can effectively suppress driveline oscillations caused by gear backlash and shaft flexibility. A combined feed-forward and feed-backward adaptive controller design is presented in [22] to reduce shaking vibration of electric vehicle, in which gear mesh stiffness and damping are further considered. Zhang et al [23] presented an active oscillation compensation strategy for electric vehicle with two-speed transmission, in which dual extended Kalman filter is used to estimate the shaft torque and torsional angle. Compared with full electric vehicle, powertrain oscillations caused by mode switching are further considered for hybrid electric vehicles [24], [25].

In current powertrain system of electric vehicles, signal communications between sensors, controllers and actuators are all realized by using controller area network (CAN) [26], [27]. Due to increasing information exchange requirement of the vehicle system, bandwidth limitation of in-vehicle network inevitably would induce time-varying delays [28], [29]. These CAN-induced delays would easily cause powertrain oscillations, which should be considered in the active damping controller design. Caruntu et al [30] presented a model predictive control approach for driveline oscillations caused by CAN-induced delays. Zhu et al [31] developed a robust controller for electrified powertrain system to achieve stable oscillation suppression in spite of CAN-induced delays. Zhang et al [32] proposed a delay compensation approach to realize oscillation damping for electric vehicles during regenerative braking. As the controller nodes of the CAN-based powertrain control system are all working in event-driven mode, the control period of each control command could be different due to the time-varying delays [31]. Thus, sampling period is intricately related to CAN-based powertrain control system so as to the oscillation damping performance. In the traditional digital control system, the sampling period is generally assumed to be constant. However, for the CAN-based control system, the sampling periods may be not fixed due to load variation of network communication [33]. Therefore, it is necessary to consider the possible sampling period change in the active oscillation controller design for IMT powertrain system over CAN, which is also the main motivation of this work.

In order to describe the system uncertainties that caused by CAN-induced time-varying delays and also sampling period changes, polytopic inclusion approach [27], [30] and norm-bounded approach [34], [35] can be adopted. For parameter-varying system with explicit upper and lower bounds, as the polytopic vertices can be directly determined, polytopic inclusion approach has been widely used in the system modeling. When the system parameters can be measured or estimated, weighting parameter of each vertex can be further calculated online and gain-scheduling controllers can be designed to improve the control performances. However, number of the vertices should be kept below certain value to avoid large online computational load. The norm-bounded approach is relatively simple, in which only the nominal values of system parameters are required. But online measured or estimated parameters could not be further used in related controller design. And similarly, the boundary of the parameter variations should not be too large. Otherwise, related system model as well as control performance would be too conservative [36]. As the CAN-induced delays are generally bounded and sampling periods are also varied at certain range, polytope with finite vertices is selected in this paper to describe the system uncertainties more precisely.

Robust control approach is an effective way to handle modeling error caused by system uncertainties and also external disturbances such as load disturbance as well as measurement noises. For the purpose of disturbance attenuation, there are generally energy-to-energy and energy-to-peak performance that are widely adopted [36]. In the energy-to-energy strategy, $L_2$ norm of the controlled output is selected to be constrained. While for the energy-to-peak strategy, $L_\infty$ norm of the controlled output is used instead. As the transient axle wrap rate is more important in the torsional oscillation control, robust energy-to-peak strategy would be a good choice in the torsional oscillation control for IMT system [31]. This paper is intended to develop a robust torsional oscillation controller for IMT system over CAN, and the major contributions can be summarized as follows:

1. In order to show the effects of CAN-induced delays under event-driven manner of the controller nodes and possible sampling period change on the torsional oscillation damping performance, a delay-free discrete-time model is developed for IMT system over CAN by using polytopic inclusion approach and system augmentation technique.

2. Based on the delay-free discrete-time model, a robust energy-to-peak controller is further developed for IMT system over CAN, which can achieve stable and good torsional oscillation suppression performance in spite of network-induced time-varying delays as well as possible sampling period change.

3. A detailed CAN model is built by using SimEvent, which can better reflect the characteristic of CAN communication. Comparative simulation tests are conducted to validate the effectiveness as well as performance of proposed torsional oscillations controller, in which conventional PI controller and energy-to-peak controller that designed with fixed sampling period are utilized.

The remainder of this paper is organized as follows. Problem formulation as well as dynamical modeling of IMT system
over CAN is presented in Section II. Robust torsional oscillation controller design is proposed in Section III. Comparative simulation tests are provided in Section IV. Finally, conclusion of this paper is presented in Section V.

II. PROBLEM FORMULATION

The topology of the IMT control system over CAN is shown in Fig.1. The IMT system is mainly composed of driving motor, two-speed automated manual transmission (AMT), differential and drive shafts. The driving motor is directly connected with the AMT without using clutch. The connections between the sensors, IMT controller unit (ICU), motor control unit (MCU) and driver are realized by using CAN as the communication medium. The referenced vehicle speed is coming from the driver module, which will be further sent to the MCU via CAN. During the control process, the sensor nodes are working in time-driven mode, while the MCU and ICU nodes are working in event-driven mode.

![Diagram of IMT control system over CAN](image)

**FIGURE 1.** Architecture of the IMT control system over CAN [30], [31].

A. BASIC DYNAMIC MODEL OF IMT SYSTEM

Without considering the wheel slip, the nonlinear air drag torque in the external load is described as [30]

\[
T_{\text{aerodrag}} = c_a \omega_w
\]

(1)

in which \(c_a\) is the linear approximation parameter, \(\omega_w\) is the wheel speed.

Selecting motor speed tracking error, wheel speed tracking error, and axle wrap tracking error of the drive shaft as system states, while motor torque error as the control input, state space model of IMT system can be described as [7], [31]

\[
\begin{align*}
\dot{x} &= A_n x + B_n (u - u^*) + E w, \\
&= \begin{bmatrix}
-c_m + c_s / J_n / f_i^2 & c_s / J_n & -k_s \\
0 & -c_s + c_a / J_w & 0 \\
1 / i_g, n_f & 1 / i_g, n_f & -1 \\
\end{bmatrix} \\
A_n &= \begin{bmatrix}
-J_n & J_n g, n_l f & J_n g, n_l f \\
0 & -c_s + c_a / J_w & 0 \\
1 / i_g, n_f & 0 & -1 \\
\end{bmatrix},
\end{align*}
\]

\[
B = \begin{bmatrix}
1 / J_n \\
0 \\
0 \\
\end{bmatrix},
\]

\[
x = \begin{bmatrix}
\omega_m - \omega_w^* \\
\omega_w - \omega_w^* \\
\theta_s - \theta_s^* \\
\end{bmatrix},
\]

\[
\theta_s = \theta_m - \theta_w, \quad u = T_m
\]

Based on referenced vehicle speed \(v^*\) and nominal vehicle load \(T_L\), desired motor rotational speed \(\omega_m^*\), wheel rotational speed \(\omega_w^*\), axis wrap angle \(\theta_s^*\), and motor torque \(T_m^*\) can be calculated in advance and sent to the controller. Although the disturbance \(w\) here is mainly caused by linear approximation of air drag torque, it can also cover other external load disturbances and modelling errors, which will be all handled by using robust controller design.

B. ANALYSIS AND DESCRIPTION OF NETWORK-INDUCED TIME-VARYING DELAYS

The IMT control system over CAN is shown in Fig. 2. With a fixed sampling period \(T_s\), the ICU node periodically collects the measurement signal from the sensor node via CAN. Due to the effect of CAN-induced delay, the measurement signal \(s(k)\) will be received by the MCU node till time \(t_1\). As the ICU node is working under event-driven mode, it will execute immediately and send the generated control command to the MCU node via CAN. Similarly, the control command will arrive at MCU node at time \(t_2\) due to network-induced delays. The MCU together with the driving motor finally will apply the torque to the IMT system. Thus, the control period of torque command \(u_k\) will start at \(t_2\) and similarly end at \(t_4\), which is time variant due to coupling effects of network-induced time-varying delays and the event-driven working mode of ICU as well as MCU node. Moreover, as the proportion between control period and sampling period may not
be an integer, it brings additional difficulties to the dynamical modeling as well as controller design for IMT control system over CAN. In order to better show the effects of network communication, discrete model is developed for IMT system over CAN.

It can be seen from Fig.2 that the control period for each torque command can be described as

$$ t \in [T_k + \tau_k, T_{k+1}] \Rightarrow T_k = kT_s $$

According to the communication protocol of CAN, the control signals will not crossed on the timeline, which can be described as [31]

$$ \tau_k \geq \tau_{k-1} - T_s $$

On the basis of the sampling period \( T_s \), CAN-induced delays can be described as

$$ \tau_k = (\bar{\tau} + \nu)T_s \quad \bar{\tau} \in \mathbb{Z}_+, \quad \nu \in \mathbb{R}_{[0,1)} $$

Thus, the discrete model of IMT system under network-induced delays can be described as

$$ x(k + 1) = A_1 x(k) + B_1 u(k) + E_1 w(k) + \Delta_{0,k}(u(k-1) - u(k)) + \Delta_{1,k}(u(k-2) - u(k-1)) + \cdots + \Delta_{\bar{\tau},k}(u(k-\bar{\tau} - 1) - u(k - \bar{\tau})) $$

where \( x \) is the upper limit of integral in system matrices \( \Delta_{i,k} \).

$$(9)$$

where \( \theta \) is the selected order in the Taylor series expansion.

Considering the CAN-induced delays are generally bounded, and the integrating ranges of system matrices \( \Delta_{i,k} \) can only be \([0, T_s]\) or \([0, \nu T_s]\), polytopic inclusion method can be applied to describe the vertices of the CAN-induced delays as

$$(10)$$

It should be noted that the sampling period \( T_s \) is assumed to be fixed in the above modeling process. However, it is not hold for networked control system, as the sampling period may be changed according to the network communication load variation [33]. Without loss of generality, it is reasonable to assume that the sampling period can be only varied in certain small range \([T_s, \min, T_s, \max]\). Thus, \( A_T \) can be similarly defined in system matrices \( \Delta_{i,k} \) as

$$ A_{T,0} = e^{AT_{t,\min}} \left[ \begin{array}{c} (-1)^{2/1} A^{0} 1! \cdots (-1)^{h+1} A^{h-1} \end{array} \right] h! \left( h! \right) $$

$$ A_{T,1} = e^{AT_{t,\max}} \left[ \begin{array}{c} (-1)^{2/1} A^{0} 1! \cdots (-1)^{h+1} A^{h-1} \end{array} \right] h! \left( h! \right) $$

Thus, the system matrix system matrices \( \Delta_{i,k} \) can be finally described as

$$(11)$$

where \( \eta_{i,m,n}(k) \) are the weighting coefficients.

Based on equation (10), other system matrices \( A_1, B_1, E_1 \) can be similarly described.

**C. CONTROL-ORIENTED DYNAMIC MODEL OF IMT SYSTEM over CAN**

In order to develop a delay-free model for IMT system over CAN, system augmentation technique is adopted and a new state variable is defined as

$$ \bar{x}(k) = \left[ x^T(k) \quad u^T(k-1) \cdots u^T(k-\bar{\tau}-1) \right]^T $$

$$(12)$$
Thus, the IMT system in equation (6) can be rewritten as
\[
\ddot{x}(k + 1) = A_2 \ddot{x}(k) + B_2 u(k) + E_2 w(k)
\]
\[
A_2 = \begin{bmatrix}
A_1 & \Delta_{a,k} - \Delta_{1,k} & \cdots & \Delta_{T-1,k} - \Delta_{T,k} & \Delta_{T,k} \\
0 & 0 & \cdots & 0 & 0 \\
0 & I & \cdots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \cdots & I & 0 \\
\end{bmatrix}
\]
\[
B_2 = \begin{bmatrix} B_1^T - \Delta_{0,k}^T & I & 0 & \cdots & 0 \end{bmatrix}^T
\]
\[
E_2 = \begin{bmatrix} E_1^T & 0 & 0 & \cdots & 0 \end{bmatrix}^T
\]

### III. TORSIONAL OSCILLATIONS CONTROLLER DESIGN

Based on the augmented system model in equation (12), a state-feedback controller structure is proposed as
\[
u(k) = K \ddot{x}(k)
\]

Thus, the closed-loop control system can be described as
\[
\ddot{x}(k + 1) = (A_2 + B_2 K) \ddot{x}(k) + E_2 w(k)
\]

**Remark 2:** As the axis wrap error is composed of integration of motor speed error and wheel speed error, the state-feedback controller design for the augmented system is actually equivalent to a PI controller design for IMT system model in equation (1).

**Remark 3:** Same controller gain \(K\) will be used for all the vertices of the convex polytope for the IMT system. Compared with gain-scheduling approaches such as Takagi-Sugeno (T-S) fuzzy control \([7]\) and linear parameter varying (LPV) control \([36]\), it may leads to conservative results. However, online calculation of the weighting coefficients can be avoided, which would be beneficial to the feasibility and practicality of the controller’s engineering implementation.

The torsional oscillations control of IMT system over CAN will be conducted during vehicle speed tracking. Thus, both the wheel speed error and axle wrap rate error are selected as the controlled outputs, which can be described as
\[
Z_i = C_1 \dot{x}(k); \quad Z_i = C_2 \ddot{x}(k)
\]
\[
C_1 = \begin{bmatrix} 0 & I & 0 \end{bmatrix}
\]
\[
C_2 = \begin{bmatrix} \frac{I}{\lambda_i} & -I & 0 \end{bmatrix}
\]

In order to reduce the torsional oscillations of IMT system during vehicle speed tracking, two robust energy-to-peak performance indexes are defined as
\[
\|Z_1\|_\infty < \gamma_1 \|w\|_2
\]
\[
\|Z_2\|_\infty < \gamma_2 \|w\|_2
\]

In order to ensure the stability of the IMT control system, following Lyapunov function is defined as
\[
V(k) = \ddot{x}^T(k) P \ddot{x}(k)
\]

Without considering disturbance \(w(k)\), the difference equation of Lyapunov function should satisfy following condition as
\[
\Delta V(k) = \ddot{x}^T(k) (\Phi^T P \Phi - P) \ddot{x}(k) < 0
\]
\[
\Phi = A_2 + B_2 K
\]

In order to further ensure the controller’s robust energy-to-peak performance, following cost function is defined as
\[
J = \sum_{i=0}^{k-1} w^T(i) w(i)
\]

By making the cost function negative and define following matrix inequalities as
\[
C^T_n C_n < \gamma_n^2 P, \quad J < 0
\]

Following condition can be obtained as
\[
Z_n^T(k) Z_n(k) = \ddot{x}^T(k) C^T_1 C_1 \ddot{x}(k) \leq \gamma_n^2 \ddot{x}^T(k) P \ddot{x}(k)
\]
\[
= \gamma_n^2 V(k) \leq \sum_{i=0}^{k-1} w^T(i) w(i) \leq \sum_{i=0}^{\infty} w^T(i) w(i)
\]
\[
J = \sum_{i=0}^{k-1} w^T(i) w(i)
\]

Thus, by using condition (20), condition (16) can be satisfied to ensure the robust energy-to-peak performance of the IMT control system. With zero initial condition, the cost function can be rewritten as
\[
J = V(k) - V(0) - \sum_{i=0}^{k-1} w^T(i) w(i)
\]
\[
= \sum_{i=0}^{k-1} \Delta V(i) - \sum_{i=0}^{k-1} w^T(i) w(i)
\]

Substituting equation (19) into (22), the cost function can be further rewritten as
\[
J = \sum_{i=0}^{k-1} \left[ \ddot{x}(i) \right]^T \left[ \Phi^T P \Phi - P \Phi^T P E_2 - I + E_2^T P E_2 \right] \left[ \ddot{x}(i) \right]
\]

By using Schur complement theory, following matrix inequality condition is given to make the cost function be negative as
\[
\begin{bmatrix}
-P & P (A_2 + B_2 K) & PE_2 \\
* & -P & 0 \\
* & * & -I
\end{bmatrix} < 0
\]

And the condition in (20) can be similarly rewritten as
\[
\begin{bmatrix}
-P & C_n^T & PE_2 \\
* & -P & 0 \\
* & * & -I
\end{bmatrix} < 0, \quad n = 1, 2
\]

In order to remove the bilinear terms, applying a congruence transformation to condition (24) by \(\text{diag} \{P^1, P^1, I\}\),
Then, following equivalent condition can be obtained as
\[
\begin{bmatrix}
-P^1 & (A_2 + B_2K)P^1 & E_2 \\
* & -P^1 & 0 \\
* & * & -I
\end{bmatrix} < 0
\] (26)

Similarly, condition (25) can be converted into
\[
\begin{bmatrix}
-P^1 & P^1 C^T \\
* & -\gamma_n^2 I
\end{bmatrix} < 0, \quad n = 1, 2
\] (27)

Further considering the vertices of the convex polytope for the system matrices, following conditions are given to ensure the stability as well as robust energy-to-peak performance of the IMT control system.
\[
\begin{bmatrix}
-P^1 & A_{2,i,j}P^1 + B_{2,i,j}Y \\
* & P^1 \\
* & * \\
* & -I
\end{bmatrix} < 0
\] (28)

By selecting appropriate Taylor series expansion order \( h \), and energy-to-peak performance indexes \( \gamma_n \), desired control gain \( K \) can be calculated by using LMI toolbox as
\[
K = Y P
\] (29)

Remark 4: Compared with the energy-to-peak controller design approach in [10], [31], utilization of projection lemma is not required for proposed controller design, by which free matrix variable \( M \) is removed in the matrix inequality condition (28). And possible sampling period change is further considered in the gain solving for proposed controller design. As the gain scheduling strategy will not be used to avoid online calculation of the weighting coefficients, only one gain matrix is required to be determined. The control gain matrix finally will be calculated by using the function ‘feasp’ in the LMI Toolbox.

IV. SIMULATION RESULTS AND ANALYSIS
Comparative simulation tests are carried out to evaluate the effectiveness as well as performance of proposed IMT controller. As it is shown in Fig. 3, simulation model for IMT control system over CAN is built in Matlab/Simulink. In order to better show the characteristics of CAN communication, a detailed CAN model is built by using Matlab/Simulink, which is composed of CAN node module and CAN bus module. The parameters of the IMT system are referred from [31]. The sampling period \( T_s \) is set by using an enable module and pulse generator. The maximum delay is set as \( 1.77T_s \). The normal sampling period \( T_{s\_min} \) is set as \( 0.01s \), while the largest sampling period \( T_{s\_max} \) is set as \( 0.06s \). The Taylor series expansion order \( h \) is set as \( 3 \). Without considering the gear shifting process, the torsional oscillations control for IMT system is conducted during vehicle speed tracking. Thus, the energy-to-peak performance index \( \gamma_1 \) is set as \( 0.02 \) to ensure the vehicle speed tracking performance. And the index \( \gamma_2 \) is set as \( 0.1 \) to reduce the torsional oscillations. By using the LMI Toolbox, the control gain is obtained as
\[
K = \begin{bmatrix}
-0.024 & -12.027 & 33.687 & 0.237 & 0.067
\end{bmatrix}
\] (30)

Considering the physical limitations of the driving motor, amplitude and changing rate of motor torque are restricted as
\[
-150N.m \leq T_m \leq 200N.m \\
-800N.m/s \leq T_{\dot{m}} \leq 800N.m/s
\] (31)

Without considering the torsional oscillation damping performance, conventional speed PI controller is used for comparative study. And the PI controller gains are selected by using trial and error method. In order to further show the performance of proposed torsional oscillations controller, the energy-to-peak controller in [31] is also adopted, in which the sampling period is fixed at \( 0.01s \) in the controller design process. With the performance index for the wheel speed error set as \( 0.07 \), and the minimum performance index for the wrap rate error is calculated as \( 0.45 \) by using the function ‘mincx’ in the LMI Toolbox. And the control gain is
\[
K_1 = \begin{bmatrix}
-0.611 & -43.316 & 195.404 & -0.200 & -0.135
\end{bmatrix}
\] (32)

As it is shown in Fig. 4, band-limited white noise is utilized to represent the measurement noises in all the sensor nodes. According to the amplitudes of motor speed, wheel speed and axis wrap angle, different noise powers are used.

![FIGURE 3. Simulation model for IMT control system via CAN.](image)

![FIGURE 4. Measurement noise in the sensor nodes.](image)
turned off, the CAN bus is working under normal network condition. The CAN bus utilization is below 0.3, and the communication delays are very small, which is just regular signal transmission time via CAN and can be ignored. When the background traffic model is set on, network congestion comes out. The CAN bus utilization is rising to around 0.5 and considerable delays appear during the signal transmission. Based on this CAN model, two scenarios are carried out to show the performance of the proposed torsional oscillation controller.

A. ACCELERATION TEST

The first simulation test is an acceleration scenario, in which the vehicle speed is expected to accelerate from 0 to 30km/h directly. The sampling period is set as 0.01s, and the background traffic model is turned off, which means the CAN bus is working under normal network condition. The vehicle speed tracking as well as torsional oscillation damping performance are shown in Fig. 7 and Fig. 8.

It can be seen that all the three controllers can meet the vehicle speed tracking performance requirement in spite of the sensor noise and external load disturbance. The torsional oscillation damping performance is almost the same for vehicle speed PI controller and proposed oscillation controller. Besides, as the settling time of the energy-to-peak controller in [31] is relative shorter during speed tracking, the torsional oscillations are accordingly larger. It can be further adjusted by selecting different performance indexes.

When the background traffic model is set on, random network-induced delays are shown as Fig. 6. Vehicle speed tracking and torsional oscillation damping performance are shown in Fig. 9 and Fig. 10.

It can be seen that desired vehicle speed can be still well tracked in spite of sensor noise and network-induced time-varying delays. By using well-tuned controller gains, the vehicle speed PI controller can also show good robust
performance. However, it fails to maintain the torsional oscillation damping performance due to network-induced time-varying delays. For the energy-to-peak controller in [31] and proposed controller, acceptable torsional oscillation damping performance can be still ensured.

Under congested network condition, in order to further show the robust performance of these three controllers under slow sampling rate, the sampling period is increased to 0.05s, which is much larger than the design sampling period for the energy-to-peak controller in [31]. Vehicle speed tracking and torsional oscillation damping performance in the presence of sensor noise, network-induced delays and sampling period change are shown in Fig. 11 and Fig. 12.

It can be seen that acceptable vehicle speed performance still can be maintained for all the three controllers. However, for the torsional oscillation damping performance, due to the effect of sampling period change, the energy-to-peak controller in [31] starts to result obvious oscillations. But it is much better than vehicle speed PI controller. While for proposed controller, good oscillation damping performance can be still ensured.

In order to show the torsional oscillation damping performance of these controllers under different network and sampling conditions, Fig.13~Fig.15 are further presented.

It is obvious that vehicle speed PI controller nearly lose its oscillations suppression capability under the influence of network-induced delays. Under the combined effects of network-induced delays and sampling period change, the performance of speed PI controller would be further deteriorated. The energy-to-peak controller in [31] can maintain its oscillations damping performance in spite of sensor noise and network-induced delays, which is apparently better than that of vehicle speed PI controller. However, it fails to cope with the combined effects of network-induced delays and sampling period change, which would result considerable oscillations. While for proposed controller, stable and good torsional oscillations can be ensured in spite of sensor noise, CAN-induced delays and also sampling period change. It shows best robust performance among these three controllers.

**B. TIP-IN TIP-OUT TEST**

Tip-in tip-out test is conducted to further show the performance of proposed controller, in which the reference vehicle speed goes from 30km/h to 1km/h and back to 30km/h again. In order to better show the performance differences of energy-to-peak controller in [31] and proposed controller, vehicle speed PI controller is not used in this test. And all the simulation tests are carried out under congested network condition.
With normal sampling period $T_s = 0.01s$, vehicle speed tracking and torsional oscillation damping performance are shown in Fig. 16 and Fig. 17.

![Figure 16](image1.png)

**FIGURE 16.** Vehicle speed tracking performance under congested network condition during tip-in tip-out test.

![Figure 17](image2.png)

**FIGURE 17.** Torsional oscillation damping performance under congested network condition during tip-in tip-out test.

It can be seen from Fig. 16 that both controllers can well track the desired vehicle speed during tip-in and tip-out test. Compared with proposed controller, the energy-to-peak controller in [31] results faster response while relatively slight overshoot. It can be seen from Fig. 17 that, both controllers can ensure stable and good torsional oscillations suppression performance during tip-in and tip-out test. And proposed controller can result relatively smaller torsional oscillations in both transit and state-steady states.

When the sampling period is set as $0.05s$, vehicle speed tracking and torsional oscillation damping performance are shown in Fig. 18 and Fig. 19.

![Figure 18](image3.png)

**FIGURE 18.** Vehicle speed tracking performance under congested network condition and slow sampling rate during tip-in tip-out test.

![Figure 19](image4.png)

**FIGURE 19.** Torsional oscillation damping performance under congested network condition during tip-in tip-out test.

Compared with proposed controller, the energy-to-peak controller in [31] demonstrates small overshoot, which is still acceptable in engineering practice. However, its torsional oscillation suppression performance distinctly falls behind that of proposed controller due to sampling period change, which fully demonstrates the advantage of proposed controller design.

During tip-in and tip-out test, it can be further seen from Fig. 20 and Fig. 21 that torsional oscillation damping performance of the energy-to-peak controller in [31] can be obviously influenced by the combined effects of network-induced delays and sampling period change. However, proposed controller can still maintain stable as well as good torsional oscillation suppression performance, which demonstrates excellent robust performance.

![Figure 20](image5.png)

**FIGURE 20.** Torsional oscillation damping performance of energy-to-peak controller in [31] during tip-in tip-out test.

![Figure 21](image6.png)

**FIGURE 21.** Torsional oscillation damping performance of proposed controller during tip-in tip-out test.

V.

**CONCLUSION**

A robust torsional oscillation controller is developed in this paper for IMT system over CAN. System nonlinearities caused by the coupling effects of controller nodes’
event-driven working mode and network-induced delays in CAN are handled by using polytopic inclusion modeling approach. And a delay-free model is developed for IMT system over CAN by using system augmentation technique. Energy-to-peak performance is adopted to restrain the negative effects of external disturbances on the robust performance of proposed torsional oscillation controller. With a detailed CAN communication model that developed by using SimEvent, two maneuvers including acceleration test and tip-in tip-out test are carried out. And the effectiveness of proposed controller is sufficiently validated by using comparative simulation tests. It shows good robust performance against sensor noise, CAN-induced delays and even sampling period change. In the future work, experimental validation such as hardware-in-loop test of proposed robust torsional oscillation controller will be further pursued.

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