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Virtual strain gauge based on a fuzzy discrete angular domain observer: Application to engine and clutch torque estimation issues

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Abstract

In many real time applications, information of transmitted torque is a mandatory input of the embedded control strategies. In the most of cases, the use of a physical torque sensor (strain gauge) is compromised by cost and bulk reasons and the torque is not measured. Unfortunately, the need of an embedded torque measurement is a general real time application problem and can only be solved through an accurate embeddable estimation method. This issue is especially common in automotive industry concerning the powertrain management for example.

A virtual strain gauge based on an unknown input Takagi–Sugeno discrete observer designed in the angular domain and a shaft angular deformation estimation method is proposed as a universal torque estimator. The static torque estimation is ensured rebuilding the shaft torsion angle by a virtual tooth adding method into the encoder sensors disposed at each edge of the shaft. The observer performs the dynamic part of the transmitted torque through a mass-spring model structure of the shaft.

The virtual strain gauge has been applied on real torque estimation issues in automotive application such as the engine and the clutch torque estimation. Simulation and real time results have permitted to validate the feasibility, the versatility and the accuracy of the virtual strain gauge.

1. Introduction

In many control applications of mechanical systems, the torque knowledge is required in order to implement closed loop strategies. Several solutions to get the torque information online exist. The simplest way to get the torque information is the measurement by a torque sensor. The so-called strain gauge is a torque sensor technology which measures the torque through the angular deformation of a shaft. This technology has been improved to contactless sensors which are used in engine control closed loop [1,2]. Unfortunately, such sensors are generally expensive and cannot be introduced on all the applications because of a problem of size. Then, another way to deal with this problem is to use embedded torque estimation methodologies.

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The online torque estimation can be realized by different ways. The most used method is based on a direct evaluation of the torque through static maps. This method is composed of two phases. The first one consists in mapping all the working points of the system and record for each point the corresponding torque. This first phase is really costly in term of experimental time. The accuracy, so the validity of the map is linked to the number of experimental points. The second phase is the implementation into the process. This methodology is commonly used in the automotive industry [3–6] to get an online engine torque estimation with the engine speed and the throttle angle as breakpoints. The main drawback of this approach is that the transient behavior is neglected.

An alternative is to consider estimation methods based on embedded dynamic models. A first solution is to implement a dynamic model which inputs are the available measured signals [7,1]. A modeling phase from data set is required using classical identification algorithms. However, for a complex system, the model parameters might change with time (ageing) or only represent a nominal behavior which causes estimator error. Another approach, considered in this article, is the design of an observer for the torque estimation problem [8–14]. A dynamic model is also needed in that context, the quality of the estimation depends on accuracy of the model but some evolution of the model can be compensated via a robust tuning of the observer parameters. Moreover, as often, a compromise must be found between the complexity of the embedded model used in the observer and the capacities of the real-time support.

In order to avoid the previously quoted problems, we proposed in this paper the development of a virtual strain gauge. Indeed, the idea is to provide a software solution to emulate a real strain gauge sensor. As a physical torque sensor, the torque estimation is based on the shaft angular torsion. The virtual strain gauge is then obtained based on two steps: first, an estimation of the angular torsion using input and output encoder sensors information is performed, and then an unknown input observer is implemented. The angular torsion estimation accuracy is a key point which is provided by a virtual tooth approach. The interest of the method is that it allows estimating a smaller angular displacement than the resolution of the sensors. The stiffness of the transmission shafts is commonly known, thus the static torque can be easily obtained. In order to deal with this angular torsion estimation, instead of consider the classical time domain, so we proposed to work in the angular domain. The nonlinearity brings by this change of derivative domain is function of the velocity of the shaft, which is bounded and measured. Hence, in order to cope with this non-linearity, the Takagi–Sugeno fuzzy representation is a perfect framework to develop our unknown input observer on angular discrete domain. With this observer, the dynamic of the torque is recovered from the angular torsion estimation and the velocity measurements. This observer and the shaft torsion estimation are synchronized with the encoder sensor to reach a better accuracy. Strength of our methodology is the simplicity of the considered model which is based on a nice mass-spring system, so the embedded observer is relatively simple and the provided methodology is independent of the considered application.

Finally, to illustrate the fuzzy virtual strain gauge efficiency, some examples of real torque estimation issues are provided in this paper. In the field of automotive when dealing with the powertrain management, the engine torque is a mandatory value used to reduce the polluting emissions and the fuel consumption. For example, the engine torque information is needed to regulate the idle speed through the control of the spark ignition [15]. This work is focused on the reduction of the idle speed engine and ensures a good disturbance rejection against the load fluctuations due to auxiliaries. More generally, the engine torque is needed to design advance engine control strategies [16,17]. The hybrid powertrain architecture tends to be generalized with the toughening of the automotive antipollution norms. This kind of powertrain combines a conventional engine and an electric motor. The aim is to assist the engine with the electric motor and in this way, foster the best operating points of the engine. To succeed in this task, an optimal strategy of both energies management is implemented. These strategies are based on a good insight of the delivered torque of each one to build a sum of torques [18–20]. Contrarily to the engine torque, the delivered electric motor torque is easy to measure or estimate accurately. Thus, the applicability of that kind of powertrain depends on the knowledge of the engine torque value. The clutch torque is also used in driveline control applications [21] to smooth the gear shifting. A recent paper [22] deals with the estimation of the torque based on a virtual crank angle sensor using a gridding of the operating using experimental trials. Our paper goes further by using a virtual torsion sensor which is a much complex problem.

This paper is articulated into four parts, the first one exposed the relation between torque and shaft angular torsion. The position of the encoder sensors on the shaft is also mentioned in this part. A general model of the system mass-spring applied to a transmission shaft is proposed. The angular torsion measurement problem and the angular torsion estimation methodology are presented in the second part with an example. The next part concerns the observer. First the link with the angular torsion estimation is explained; next the observer model is introduced. The synthesis of the

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