Optical–Ultrasonic Heterogeneous Sensor Based on Soft-Computing Models

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***Abstract*— A heterogeneous sensor system to determine the ethanol concentration in ethanol–water solution is demonstrated. The system consists of an optical-fiber refractometric transducer based on a long-period grating and a pair of ultrasonic transducers in transmission–reception mode, connected to a stand-alone electronic board for data acquisition, storage, and signal preprocessing. To implement a coherent sensor fusion from both measurement techniques, two soft computing methods (artificial neural network model and neuro-fuzzy model) are studied. A comparative analysis of these models was carried out based on the measured data. The best performance was obtained with the neural-network-based model. This model showed that it was able to correlate the responses of the optical-fiber transducer and the ultrasound system with the ethanol–water concentration. The final performance of the heterogeneous system is better within the whole range of concentrations, even if compared with the best performance of the individual sensors for limited ranges.**

***Index Terms*— Concentration measurement, data fusion, ethanol sensor.**

I. INTRODUCTION

ETHANOL is used in several industrial sectors such as beverage, pharmaceutical, and chemical. In the fuel industry, ethanol is widely employed either as a fuel or a gasoline additive. Due to its high solubility in water, an effective and fast determination of water content in ethanol is fundamental to assure the product quality. As ethanol is added to water, interactions between the molecules lead to changes in the molecular structure of the compounds. This behavior is probably due to the formation of clusters driven by chemical kinetics that is dependent upon the relative concentration of the sample constituents. As a result, a variation in the final volume of the sample occurs [1]. Owing to this volume dependency, physicochemical parameters like refractive index or sound velocity in the sample present a nonlinear behavior depending on the ethanol concentration in the blend.

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Therefore, operational difficulties arise when the methods proposed for the ethanol content determination are based on the measurements of such parameters that exhibit a complex dependency on the ethanol and water proportions in the mixture. In spite of this limitation, refractometric determination of ethanol–water concentration in binary samples has been reported in the literature. Shu *et al.* [2] employed a long-period fiber grating (LPG) as a refractive index transducer for ethanol–water measurement. A minimum detectable concentration change of 0.2% v/v for the ethanol concentration range between 0% and 60% v/v was estimated. The splitting between two resonant modes in the transmission spectrum was used as a parameter for concentration characterization.

In [3], the ethanol–water concentration in the range between 0% and 100% v/v was measured by means of an LPG coded both in wavelength and intensity. The ambiguous response issue was addressed by means of two linear approximations fitted to different regions of the sensor response curve and performing controlled addition of water to the samples under analysis. The best obtained resolution was 0.23% v/v for ethanol concentrations ranging from 89.6% to 100% v/v [3]. Although several fiber-based refractometers have been successfully demonstrated in the past years, an important feature that cannot be disregarded in the sensor performance is its cross sensitivity to multiple measurands. Although the inherent cross sensitivity of optical-fiber grating-based sensors is recognized as a usual drawback, it has been successfully employed to decouple the parameters under measurement [4]–[6].

Studies related to the analysis of ethanol–water mixtures were also reported using ultrasonic techniques. D'Arrigo and Paparelli [7] analyzed ultrasonic velocity measurements in ethanol aqueous solutions from +30 °C to −40 °C over the entire blend composition range (0%–100% v/v) and in the frequency range 10–70 MHz. As a result, they proposed a model to explain volumetric properties of ethanol mixtures in low temperatures and low concentration ranges of the solute. Identification of alcohol type and volume concentration in water–ethanol/methanol binary mixtures with ultrasonic velocity measurements was carried out [8]. Ultrasonic techniques were also applied in the fuel industry by Chakhlov *et al.* [9] to monitor the density of petroleum products, with an accuracy of about 1 kg/m^3. From the experimental data analysis, the authors also showed that the velocity of propagation of ultrasonic waves is inversely proportional to the temperature for different liquids. Moreover, this reduction in the velocity of ultrasonic waves is about 4.0–5.5 m/s per degree.