

Profile Monitoring with Fixed and Random Effects using Nonparametric and Semiparametric Methods

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Abstract

Profile monitoring is a relatively new approach in quality control best used where the process data follow a profile (or curve) at each time period. The essential idea for profile monitoring is to model the profile via some parametric, nonparametric, and semiparametric methods and then monitor the fitted profiles or the estimated random effects over time to determine if there have been changes in the profiles. The majority of previous studies in profile monitoring focused on the parametric modeling of either linear or nonlinear profiles, with both fixed and random effects, under the assumption of correct model specification.

Our work considers those cases where the parametric model for the family of profiles is unknown or at least uncertain. Consequently, we consider monitoring profiles via two techniques, a nonparametric technique and a semiparametric procedure that combines both parametric and nonparametric profile fits, a procedure we refer to as model robust profile monitoring (*MRPM*). Also, we incorporate a mixed model approach to both the parametric and nonparametric model fits. For the mixed effects models, the *MMRPM* method is an extension of the *MRPM* method which incorporates a mixed model approach to both parametric and nonparametric model fits to account for the correlation within profiles and to deal with the collection of profiles as a random sample from a common population.

For each case, we formulated two Hotelling's T^2 statistics, one based on the estimated random effects and one based on the fitted values, and obtained the corresponding control limits. In addition, we used two different formulas for the estimated variance-covariance matrix: one based on the pooled sample variance-covariance matrix estimator and a second one based on the estimated variance-covariance matrix based on successive differences.

A Monte Carlo study was performed to compare the integrated mean square errors (*IMSE*) and the probability of signal of the parametric, nonparametric, and semiparametric approaches. Both correlated and uncorrelated errors structure scenarios were evaluated for varying amounts of model misspecification, number of profiles, number of observations per profile, shift location, and in- and out-of-control situations. The semiparametric (*MMRPM*) method for uncorrelated and correlated scenarios was competitive and, often, clearly superior with the parametric and nonparametric over all levels of misspecification. For a correctly specified model, the *IMSE* and the simulated probability of signal for the parametric and the *MMRPM* methods were identical (or nearly so). For the severe model misspecification case, the nonparametric and *MMRPM* methods were identical (or nearly so). For the mild model misspecification case, the *MMRPM* method was superior to the parametric and nonparametric methods. Therefore, this simulation supports the claim that the *MMRPM* method is robust to model misspecification.

In addition, the *MMRPM* method performed better for data sets with correlated error structure. Also, the performances of the nonparametric and *MMRPM* methods improved as the number of observations per profile increases since more observations over the same range of X generally enables more knots to be used by the penalized spline method, resulting in greater flexibility and improved fits in the nonparametric curves and consequently, the semiparametric curves.

The parametric, nonparametric and semiparametric approaches were utilized for fitting the relationship between torque produced by an engine and engine speed in the automotive industry. Then, we used a Hotelling's T^2 statistic based on the estimated random effects to conduct Phase *I* studies to determine the outlying profiles. The para-

metric, nonparametric and seminonparametric methods showed that the process was stable. Despite the fact that all three methods reach the same conclusion regarding the “in-control” status of each profile, the nonparametric and *MMRPM* results provide a better description of the actual behavior of each profile. Thus, the nonparametric and *MMRPM* methods give the user greater ability to properly interpret the true relationship between engine speed and torque for this type of engine and an increased likelihood of detecting unusual engines in future production. Finally, we conclude that the nonparametric and semiparametric approaches performed better than the parametric approach when the user’s model is misspecified. The case study demonstrates that, the proposed nonparametric and semiparametric methods are shown to be more efficient, flexible and robust to model misspecification for Phase *I* profile monitoring in a practical application.

Thus, our methods are robust to the common problem of model misspecification. We also found that both the nonparametric and the semiparametric methods result in charts with good abilities to detect changes in Phase *I* data, and in charts with easily calculated control limits. The proposed methods provide greater flexibility and efficiency than current parametric methods used in profile monitoring for Phase *I* that rely on correct model specification, an unrealistic situation in many practical problems in industrial applications.