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Functional Data Analysis and Classification for Profile Monitoring and Fault Diagnosis in Waterjet Machining Processes

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Abstract

In the frame of manufacturing processes, quality characteristics may often be represented in terms of a spatially or time ordered data. Whenever the goal is to monitor the stability over time of a repeating pattern, an important issue is represented by curve registration. Usually, registration is performed in the pre-processing step, and then profile monitoring methods are applied on the resulting curves. ***This study investigates the possible benefits of coupling the profile registration and profile monitoring approaches****, by monitoring, at the same time, the coefficients of a parametric model of the signal and the coefficients of the warping function used for registration.*

A Real Test Case: High Pressure Waterjet Cutting

A real test case is considered to evaluate the approach: the in-process monitoring of pressure signals in **Waterjet (WJ) machining processes**.

High pressure WJ cutting, with or without abrasive additive, is an unconventional machining process that is being used in nearly every manufacturing sector today, from aerospace to the food and textile industry.

The **pressure signal** is characterized by a repeating pattern in time, consisting of dynamic pressure oscillations around the static level. Designed experiments were performed to collect real data both under natural process conditions and in presence of actual faults.

The Profile Monitoring Approach

The term "*profile monitoring*" refers to the stability analysis of a **functional relationship between a response variable and one or more explanatory variables**. In this frame, functional data analysis is used to characterize the pattern of signal profiles whose repetition, under in-control conditions, should be stable over time.

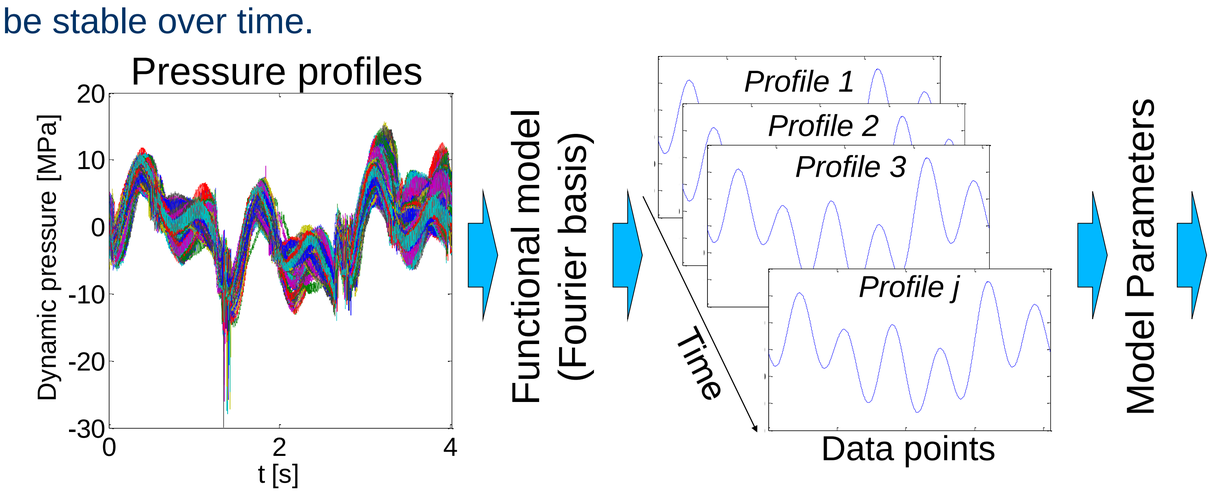

Fig 1 – Scheme of profile monitoring method applied to WJ pressure profiles

Functional Analysis of Pressure Signals

A **Fourier basis** was chosen to smooth the profiles and to estimate a model able to characterize normal health conditions. The first six harmonics are included into the model. A **Time Warping approach** was used for curve registration. Warping functions are **third degree polynomial functions**.

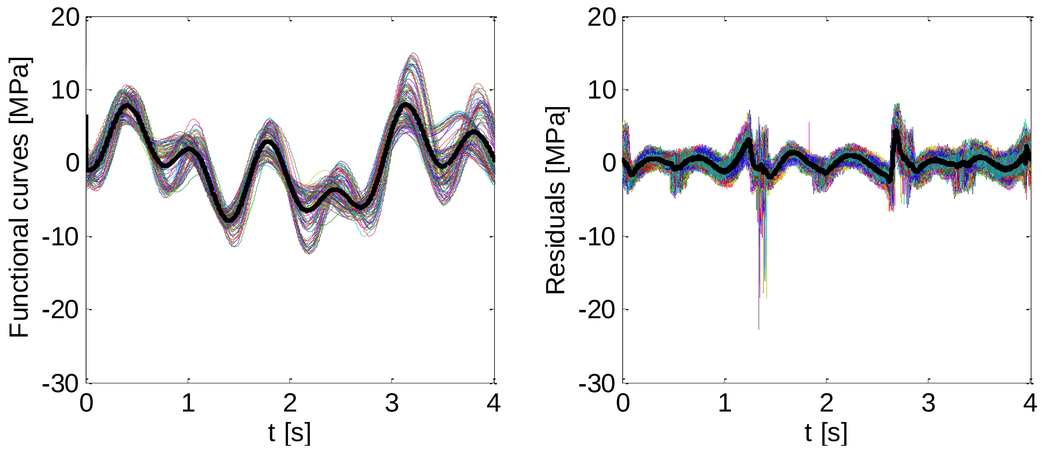

Fig 2 – Functional curves (not registered) and model residuals

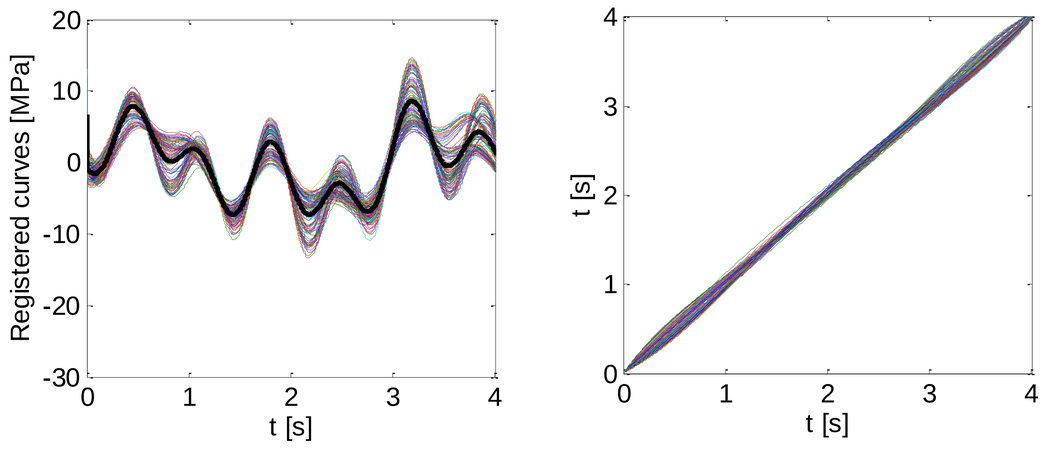

Fig 3 – Registered curves and estimated time warping functions

Results

Profile monitoring performances are compared with a more conservative method applied in industry, which consists of computing synthetic indexes and applying a multivariate control chart on them (*index-based approach*). Table 1 shows that the **profile monitoring approach outperforms the index-based approach**. Moreover, curve registration and inclusion of warping coefficients into the monitored vector allows achieving the highest performances. Fig. 4 shows that the analysis of warping coefficients provides additional diagnostic information to support the fault classification task.

Monitoring Approach		Faulty Detection Percentage (%)				
		Fault *a*	Fault *b*	Fault *c*	Fault *d*	Tot
Index-based		50.00	5.88	2.63	50.57	30.41
Profile Monitoring	I) Un-registered curves	100	92.16	65.79	90.80	87.16
	II) Registered curves (only Fourier coeff.s monitored)	100	68.63	69.74	78.16	80.41
	III) Registered curves (both Fourier & warping coeff.s monitored)	**100**	**100**	**88.16**	**100**	**96.96**

Table 1 – Fault detection percentage in different scenarios

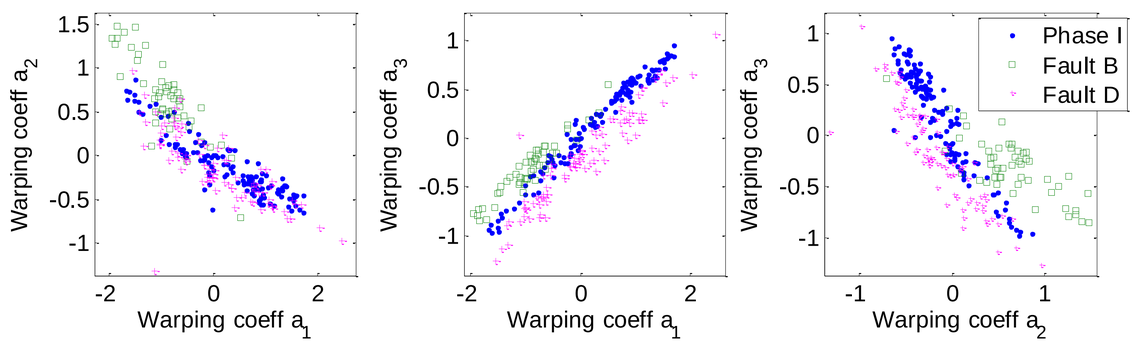

Fig 4 – Effect of two faults on warping coefficients

Conclusions

Curve registration plays a fundamental role in profile monitoring problems. The study shows that **by merging the functional coefficients of registered profiles with the functional coefficients of warping functions used for registration, the detection performances may be improved**, since the information loss is minimized. Finally, the analysis of warping parameters is expected to provide additional useful information to support the fault diagnosis.

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