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Shaper-Based Filters for the compensation of the load cell response in dynamic mass measurement

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ABSTRACT

This paper proposes a novel model-based signal filtering technique for dynamic mass measurement through load cells. Load cells are sensors with an underdamped oscillatory response which usually imposes a long settling time. Real-time filtering is therefore necessary to compensate for such a dynamics and to quickly retrieve the mass of the measurand (which is the steady state value of the load cell response) before the measured signal actually settles. This problem has a big impact on the throughput of industrial weighing machines. In this paper a novel solution to this problem is developed: a model-based filtering technique is proposed to ensure accurate, robust and rapid estimation of the mass of the measurand. The digital filters proposed are referred to as Shaper-Based Filters (SBFs) and are based on the convolution of the load cell output signal with a sequence of few impulses (typically, between 2 and 5). The amplitudes and the instants of application of such impulses are computed through the analytical development of the load cell step response, by imposing the admissible residual oscillation in the steady-state filtered signal and by requiring the desired sensitivity of the filter. The inclusion of robustness specifications tackles effectively the unavoidable uncertainty and variability in the load cell frequency and damping. The effectiveness of the proposed filters is proved experimentally through an industrial set up: the load-cell-instrumented weigh bucket of a multihead weighing machine for packaging. A performance comparison with other benchmark filters is provided and discussed too.

1. Introduction

Load cells are sensors widely employed for performing dynamic weighing, i.e. to compute accurately and rapidly the value of the measurand while the sensor output is still in oscillation and before stable equilibrium is achieved. There are several industrial applications where dynamic and automatic weighing is requested. Challenging examples are multihead weighing machines, extensively employed, for example, in the food industry, where load-cell-instrumented weigh buckets should measure accurately and very quickly the weight of parts falling from accumulation chambers or conveyors above the buckets. To cope with the underdamped oscillatory response of load cells and with the presence of impulsive and step-like excitations, signal filtering is essential since the use of active or passive control techniques to increase damping is very complicate, expensive and often not effective. Indeed, active control would require control forces and hence actuators (see e.g. [1]), while passive damping through dampers increases the rise time of the measured signals. Effective filters should be

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therefore synthesized to ensure a short settling time, no steady-state error, robustness with respect to the unavoidable uncertainty and variability of the system physical parameters, and finally ease of implementation, small computational effort and memory allocation to guarantee real-time processing.

In dynamic mass measurement, the synthesis of filters is a critical and not trivial task. Indeed, by solely decreasing filter bandwidths to cut high frequency disturbances one usually increases settling times and hence downgrades the measurement speed and the throughput of the machine using such filters. Besides the general-purpose filters developed in the field of signal processing (such as the well-known Bessel or Butterworth filters), some filtering techniques have been specifically addressed to load cell response correction. Model-based filtering schemes have been often synthesized in the literature. Adaptive schemes have been proposed in [2,3] to perform pole-zero cancellation or to optimally trade-off between bandwidth and settling time [4]. The use of a Kalman-filter has been exploited in [5] for objects moving on a weighing table with known speed. A filtering technique based on an array of accelerometers has been proposed in [6] to remove the low frequency components in load cell signals that are due to the frame flexibility. A different type of approach is the synthesis of non-model based filters, such as those using neural networks [7], recursive least-square procedures [8], model-free discrete non-stationary or time-variant filters [9–12].

In the light of the previous requirements, this paper proposes a novel model-based filtering technique which is devoted for dynamic weighing through load cells. The proposed method takes advantage of the idea of the Input Shaping feedforward control (IS), that has been developed for the optimal planning of command position references in flexible systems (see e.g. [13–15]). The original application of IS is motion control of trolley-pendulum systems, such as cranes. IS physically modifies the actuator force or the trolley displacement to ensure zero residual load oscillations after the end of the crane motion. Hence it is a motion planning technique, that can be thought of as an open-loop control. Motion planning through IS relies on the convolution of the actuator force or of the position reference of the crane with a sequence of a few impulses, referred to as the shaper, to modify the crane trajectory in time so that load swing is controlled. The idea of convolving a signal with a baseline of few impulses to compensate for elastic oscillation is here assumed as the starting point to develop a new filtering technique for load cells. Rather than being convolved with a physical input, as in the IS, the sequence of impulses is here convolved with the system output, that is the load cell measured signal. These filters are denoted Shaper-Based Filters (SBFs) and, to the best of the Author's knowledge, no extension of the IS theory in the field of signal processing can be found in literature. SBFs are online signal processing schemes employed to quickly retrieve the steady state value of the load cell signal before it settles. In contrast with the original idea of IS, the filters proposed in this work are not employed to perform a physical modification of the input exciting the flexible system, which is not allowed in weighing operations.

The filtering scheme proposed fits well the requirements of short settling time, accuracy and robustness. The potential benefits of this kind of filters includes also ease of tuning, low computational effort and small memory required, since filtering relies on the convolution of the measured signal with just a few impulses. All these features make the proposed SBFs suitable for real-time signal processing, as required in industrial weighing machines.

The paper is organized as follows: Section 2 proposes the synthesis of the simplest form of a SBF, starting from load cell dynamic model. The robustness issue is discussed in Section 3 and robust filters are synthesized. An experimental verification of the effectiveness of the proposed filters is proposed in Section 4 by means of an industrial set up: the load-cell-instrumented weigh bucket of a multihead weighing machine for food packaging. In the same Section a comparison with the results obtained employing other popular filtering techniques is provided. Concluding remarks are finally given in Section 5.

2. Basic theory of Shaper-Based Filters

2.1. Load cell model

The filter synthesis takes advantage of load cell dynamic model. For this purpose, the dynamic behavior of load cells commonly used in weighing devices, such as strain-gauge load cells, can be modeled through a single degree-of-freedom lumped model (whenever they are fixed on a rigid frame). If the sensor transverse sensitivity is neglected and the elastic behavior is linear, as it is common in practice, the second-order spring-damper-mass system model can be assumed (see e.g. [6]):

$$\ddot{\varepsilon}(t) + 2\xi\omega_N\dot{\varepsilon}(t) + \omega_N^2\varepsilon(t) = \gamma\omega_N^2 M(t) \tag{1}$$

where $\varepsilon(t)$ is the load cell response (i.e. the measured signal), γ is the load cell static gain, and $M(t)$ is the measurand mass. By assuming a lumped parameter model the natural frequency ω_N, and the damping ratio ξ are defined as:

$$\omega_N(t) = \sqrt{\frac{k}{M_c + M(t)}}, \quad \xi(t) = \frac{c}{2\sqrt{k(M_c + M(t))}} \tag{2}$$

In Eq. (1), k and c are, respectively, the constant load cell equivalent linear stiffness and damping coefficient in the measuring direction. M_c is the equivalent mass of the empty load cell, which comprises the contribution of the uniformly distributed mass of the sensor and the mass of the bucket. Fig. 1 sketches the system studied.