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Hardware implementation of auto-mutual information function for condition monitoring☆

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ABSTRACT

This study is aimed at showing the applicability of mutual information, namely auto-mutual information function for condition monitoring in electrical motors, through age detection in accelerated motor aging. Vibration data collected in artificial induction motor experiment is used for verification of both the original auto-mutual information function algorithm and its hardware implementation in Verilog, produced from an initial version made with MATLAB HDL (Hardware Description Language) Coder. A conceptual model for industry and education based on a field programmable logic array development board is developed and demonstrated on the auto-mutual information function example while suggesting other applications as well. It has also been shown that attractor reconstruction for the vibration data cannot be straightforward.

1. Introduction

The question of motor age identification using vibration signals has been studied thoroughly in the past [1,2]. Methods based on dynamical systems theory have been proposed [3], but they ask for more thorough insight, which is provided in this paper. This study provides an analysis of dynamical system properties of artificial motor aging vibration data, a novel method for age detection and an implementation of this method in an innovative conceptual model.

Regarding realization, the idea of condition monitoring algorithm implementation in hardware is not new [4-6]. There have been efforts to implement some new and specific algorithms in hardware, but some classical algorithms have been neglected as their applicability to condition monitoring was not acknowledged. Implementations so far, as in general case of condition monitoring as well, have been focused on machine learning [4], while the work presented here will focus on a signal processing technique from the dynamical systems theory.

In work presented here, we introduce a novel framework for condition monitoring prototyping and training, which we use as the platform for a hardware implementation of auto-mutual information function calculator. While it is usually used in dynamical systems theory for attractor reconstruction, here we show that the auto-mutual information function is a good indicator of motor state, when applied to its vibration signals.

In the second section of the paper, we present the fundamental concepts our implementation relies on: the auto-mutual information function, hardware description and the problem of the artificial motor aging. While describing the listed con-

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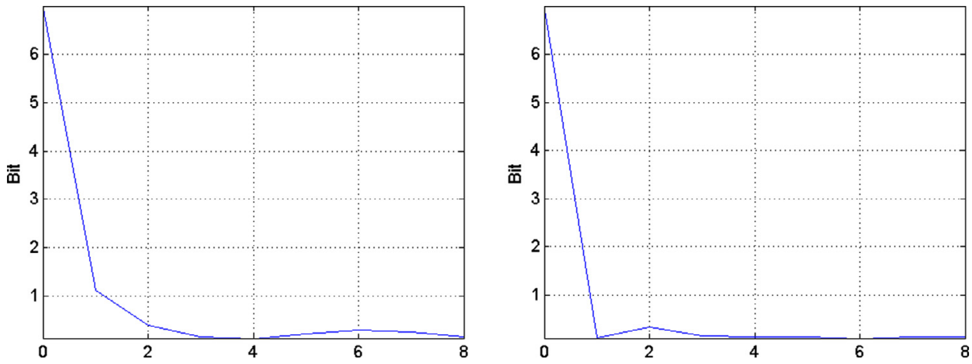

Fig. 1. Auto-mutual information function for vibration series 0 (a) and 7 (b).

cepts, we also discuss the way we implement them. In the third section, we show the results of our proposed solution applied to two fundamentally different problems of condition monitoring, artificial and non-artificial motor aging. Finally, we discuss the results obtained before drawing conclusions and implications for future work.

2. Materials and methods

2.1. Auto-mutual information function

To calculate Lyapunov exponents which are suggested as a feature useful for motor condition determination in earlier work [3], the attractor has to be reconstructed. Since in general, we do not have more than one or at most two time series from the process (and the underlying dynamics have higher dimensions), other coordinates in phase space need to be generated. A common approach is one using a delayed version of the existing coordinates and applying the Takens theorem [7]. This method depends heavily on two parameters, the delay time and the embedding dimension.

There is no optimal algorithm for these parameters, but some plausible approaches were introduced. For example, the delay time can be determined using auto-mutual information function [8], while a false neighbor-like approach can be used for embedding [9]. After this attractor reconstruction, the Lyapunov exponent can be calculated. The most used algorithm for that is one proposed in [10], but others have been proposed as well, such as Sato's [11], which is the algorithm for Lyapunov exponent calculation in MATLAB compatible OpenTSTOOL software [12] based on non-linear time series algorithms and methods presented in [13].

As the auto-mutual information function (AMIF) is going to be used extensively in this letter, it will be defined here.

For systems S and Q with discrete states s_1,s_2,..., s_n and q_1,q_2,..., q_m with respective probabilities $P_s(s_1)$,..., $P_s(s_n)$ and $P_q(q_1)$,..., $P_q(q_m)$ the mutual information function $I(Q, S)$ is the number of bits of q that can be predicted on average given a measurement of s:

$$I(Q,S) = \sum\sum P_{sq}\left(s_i q_j\right)\log\frac{P_{sq}\left(s_i q_j\right)}{P_s(s_i)P_q\left(q_j\right)} \tag{1}$$

where $P_{sq}(s_i,q_j)$ is the probability that $s=s_i$ and $q=q_j$. In order to apply this in experimental data, P_{sq} is to be estimated by partitioning of $S-Q$ plane into elements. P_{sq} is represented by the ratio of the number of points in an element and the total number of points.

After obtaining the first minimum of the auto-mutual information function (seen in a graphical representation in Fig. 1 for a motor vibration signal), its index can be used as the delay time for generation of other coordinates in the phase space. Cao's dimension estimation algorithm is applied to determine the number of such coordinates. Abscissa value where its characteristic d_1 drops for the first time denotes the embedding dimension. Furthermore, its d_2 characteristic is used for determinism checking: it is constant in case of pure stochastic signals. After these two parameters (delay time and embedding dimension) are acquired, the reconstruction is straightforward.

At that point, the Lyapunov exponents can be calculated by applying any of the proposed algorithms. Namely, the Sato's algorithm finds the Lyapunov exponent for the time series as the slope of the particular probability curve in its rising part.

2.2. Hardware description

Since this research is not conducted on a dedicated motor testbed, this practical implementation should have the possibility to be verified using the existing data records in a Hardware-in-loop (HIL) setup. Validation of condition monitoring methodologies in HIL setup has been done before, so it can be considered a reliable procedure [14].

While a generalized form of this device will be discussed in this subsection, a particular algorithm (auto-mutual information function) is chosen as a proof of concept to be implemented for demonstration purposes.

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