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The Predictability of a Target Signal Affects Manual Feedforward Control

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Abstract: In the manual control of a dynamic system, the human controller (HC) is often required to follow a visible and predictable reference path. Using the predictable aspect of a reference signal, through applying feedforward control, the HC can significantly improve performance as compared to a purely feedback control strategy. A proper definition of a signal's predictability, however, is never given in literature. This paper investigates the predictability of a sum-of-sinusoids target signal, as a function of the number of sinusoid components and the fact whether the sinusoid frequencies are harmonic, or not. A human-in-the-loop experiment was done, with target signals varying for these two signal characteristics. A combined feedback-feedforward HC model was identified and parameters were estimated. It was found that for all experimental conditions, subjects used a feedforward strategy. Results further showed that subjects were able to perform better for harmonic signals as compared to non-harmonic signals, for signals with roughly the same frequency content. *Copyright ©2016 IFAC*

Keywords: Cybernetics, manual control, feedforward control, parameter estimation

1. INTRODUCTION

Manual control often requires a Human Controller (HC) to steer a dynamic system along a certain reference path while being perturbed by a disturbance. An example is riding a bicycle on a winding road, where the road is the 'target' trajectory and the wind is the 'disturbance'. Several information sources are used to control the bicycle, such as visual, vestibular, somatosensory and proprioceptive information about the current state of the bicycle, but also the visual information of the road ahead. In many everyday manual control situations, the human controller has prior information about the route that has to be followed. If the cyclist travels a familiar route, there is information about the target path from memory. In this case the target path is known and the controller can use this information to optimize performance without decreasing stability.

Previous manual control research focused on the HC tracking either very predictable target signals, e.g., signals which consist of only one or two sine waves (Pew et al., 1967; Yamashita, 1989) or very unpredictable signals, such as the well-known *quasi-random* forcing functions which contain at least ten sine waves (Wasicko et al., 1966; McRuer and Jex, 1967). These studies did not give a clear definition, however, for the predictability of the target signal. They merely stated that the target signal was predictable, or not. A thorough understanding of factors that may affect the human's ability to predict the (near) future of the target signal is not available. This lack of knowledge stands in stark contrast with the well-known fact that a HC's control strategy changes significantly when the target signal becomes predictable. Hence, it is our objective in this paper to perform a first investigation into what factors affect the predictability of target signals used for manual control experiments.

For several decades, three different control strategies have been distinguished for tracking tasks, described first in (Krendel and McRuer, 1960) in their successive organization of perception (SOP) scheme: compensatory, pursuit and precognitive control. The *compensatory* control strategy is based on controlling a dynamic system purely on the error e, defined as the difference between the target signal f_t and the controlled element (CE) output θ: $e = f_t - \theta$. With a compensatory display, the HC simply aims at minimizing the error. When the target signal is unpredictable, the control strategy is feedback-only.

In *pursuit* tracking, more information is presented to the HC. Here, with a pursuit display, the target signal and system output are explicitly shown, allowing the HC to infer error from the difference between both signals, and to act on all three possible inputs in some way to improve tracking performance. In (Wasicko et al., 1966) it was first reported that, for the majority of the considered CE dynamics, the HC control strategy changes considerably, and performance improves, suggesting that the HC applies a feedforward control on the target signal, combined with a feedback on the error. At the highest level of the SOP, *precognitive* control, the HC operates in an 'open loop', pure feedforward mode on the target signal. It is assumed that the HC has complete information about the target

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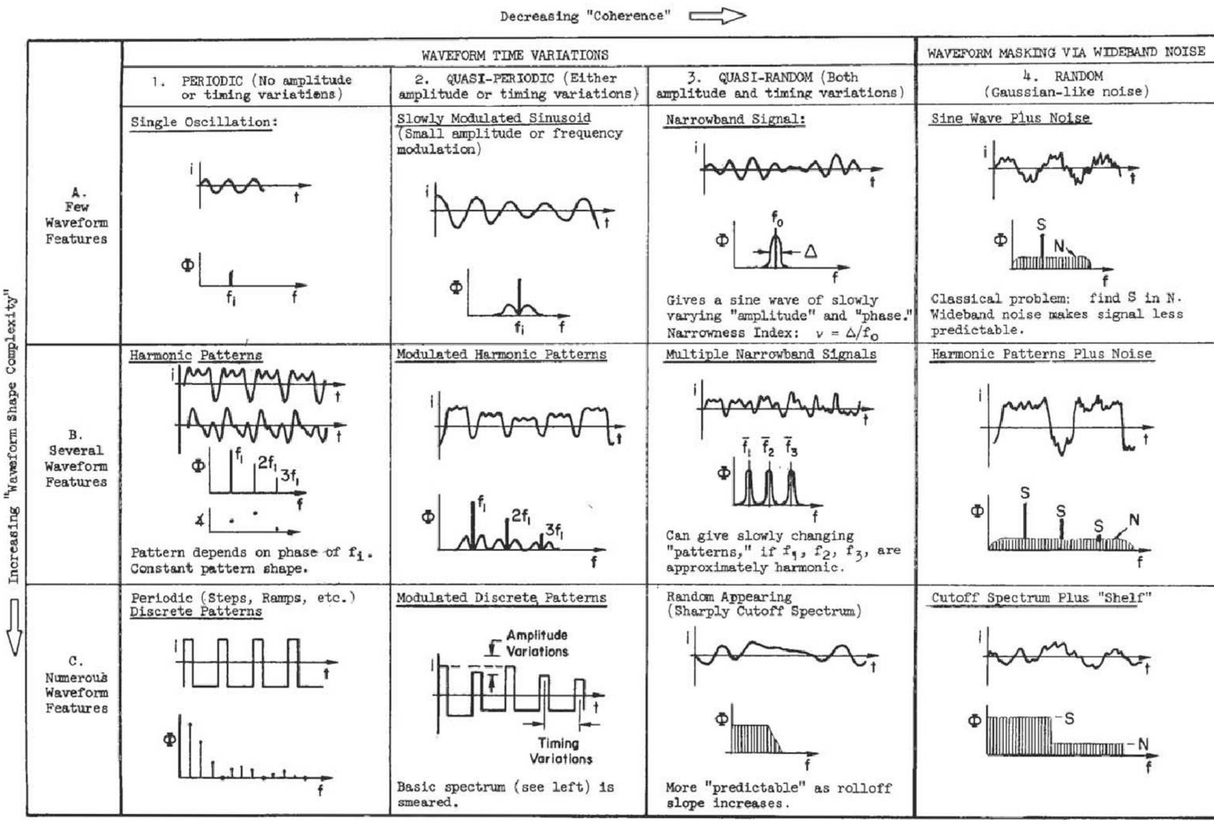

Fig. 1. The levels of (subjective) predictability as proposed in (Magdaleno et al., 1969).

(visually, e.g., when presented on a preview display, or in memory, when the HC has memorized the target), as well as close-to-perfect knowledge of the system dynamics, and little to no feedback is needed.

In (Magdaleno et al., 1969) these three control strategies were studied, and for the first time an attempt was made to look at how the shape of the target signal affects the control strategy adopted by the HC, see Figure 1. One of the main hypotheses stated, was that HCs can reach higher SOP levels at an earlier stage when the target signals become more and more predictable. This hypothesis, however, was not experimentally verified.

Recently, system identification and parameter estimation methods have become available to obtain objective evidence for the claims reported in (Wasicko et al., 1966) and (Magdaleno et al., 1969). Different methods to objectively measure and model the HC feedforward behavior were developed in (Drop et al., 2013; Laurense et al., 2015). In this paper these methods are used to identify the strength of the HC feedforward path, as a function of the level of predictability of the target signals. From the many possible dimensions to be investigated (see (Magdaleno et al., 1969) for a complete overview) two particular characteristics of a sums of sinusoids target signal were studied: (i) the number of sinusoid components, and (ii) the use of harmonic components in the target signal, or not.

For this purpose, a human-in-the-loop tracking experiment was conducted. Apart from the objective measurement of the HC feedforward-feedback control behaviour from the experimental time traces, the level of predictability was also measured in a subjective way, by asking the participants their opinion of the signal's predictability.

The paper is structured as follows: Section 2 provides more background information on the predictability of signals in tracking experiments. Section 3 describes the HC model structure and model parameters, which are used to characterize the observed control behavior. Section 4 describes the experiment, the results of which are presented in Section 5. The paper ends with conclusions.

2. SIGNAL PREDICTABILITY

2.1 Introduction into Predictability

In (Magdaleno et al., 1969) it is hypothesized that a predictable target signal will make the HC able to reach the pursuit and precognitive phases of the SOP in an earlier stage, yielding a better performance. The first ideas to categorize target signals by their level of predictability was also done by Magdaleno et al., who used three dimensions: (i) waveform shape complexity, (ii) waveform time variations, and (iii) waveform masking by noise.

The waveform *shape complexity* means that in tracking a forcing function with a repetitive pattern, subjects first focus on getting the correct 'directions' of the signal, then on the 'timing' and finally (and to a lesser extent) the 'amplitude'. Regarding the waveform *time variations*, it is either the amplitude or the frequency of the target signal that will change over time, e.g., in amplitude- or frequency-modulated signals. If the variation in time is large, the signal becomes less predictable, as compared to a smaller