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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.

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

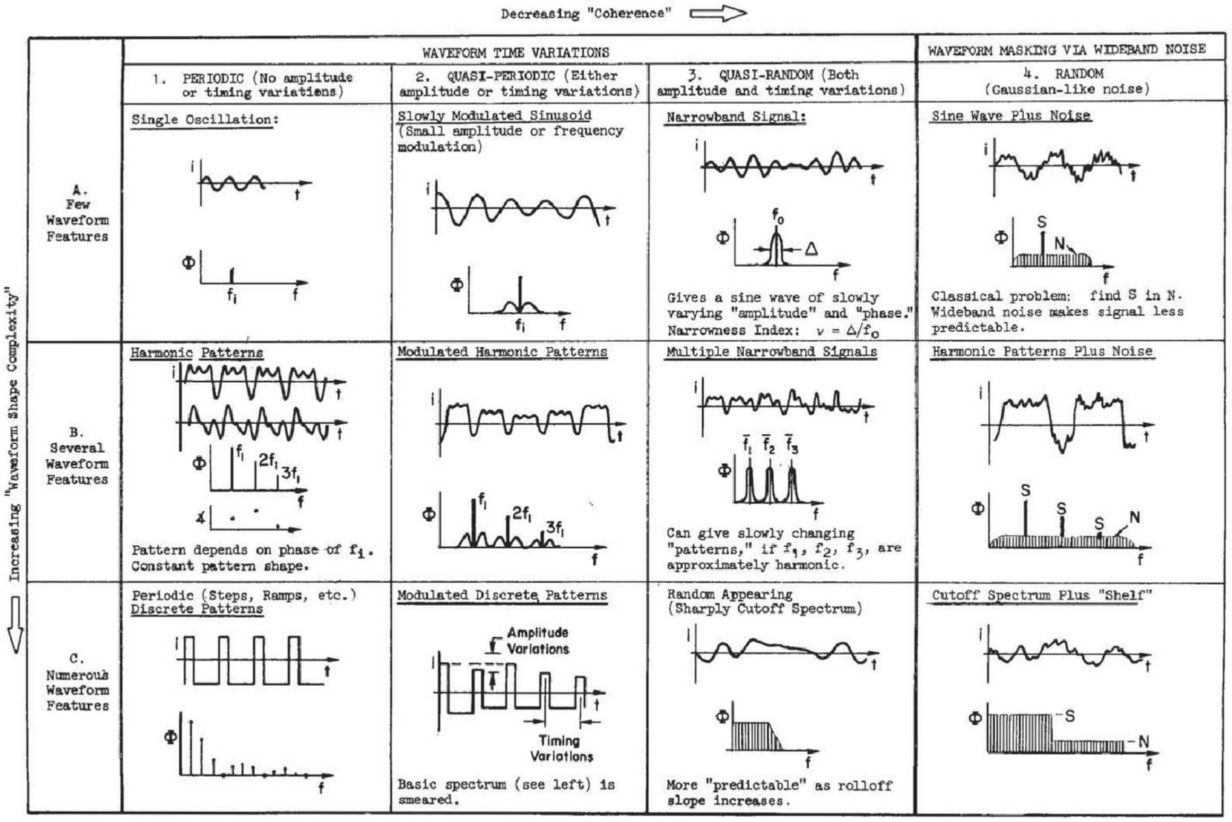


Fig. 1. The levels of (subjective) predictability as proposed in (Magdaleno et al., 1969).

(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 variation in time. Considering the waveform *masking by noise*, colored noise is added in the frequency region of the target signal. Possible metrics for predictability are then the signal-to-noise ratio and various coherence functions.

With these dimensions in mind, Magdaleno et al. presented a table with the different gradings for the (subjective) predictability (Magdaleno et al., 1969), see Figure 1. Signals in the top left corner (Category A-1) are assumed to be the most predictable; signals in the lower right corner (Category C-4) are the least predictable signals. Although providing great insight, none of these claims were experimentally validated. In this paper we will study only the harmonic patterns (Category B-1).

2.2 Harmonic and Non-harmonic Signals

For a sine wave with fundamental frequency f_0, the harmonic frequencies are those with a frequency that is an integer multiple of f_0 ($2f_0$, $3f_0$, ...). Signals where all components are harmonics of the lowest frequency are called harmonic signals. If this is not the case, it is a non-harmonic signal. Harmonic signals show a repetitive pattern with a shorter period than the non-harmonic signals.

We aim to study the effect of a signal being harmonic (H) or non-harmonic (NH). The sinusoid frequencies were chosen in such a way that eight periods of the harmonic signals fit in one experimental run (with measurement time T_m=81.92 s). The period of the non-harmonic signals was equal to the measurement time. In addition, signals either consisted of $N_t = 2$, 3 or 4 sinusoid components with different frequencies. This yields six possible target signals (2H, 3H, 4H; 2NH, 3NH, 4NH) that will act as the main independent variable in our investigation.

Table 1. Target signal properties.

Harmonic (H)			Non-Harmonic (NH)		
n_t	$\omega_t, rad \cdot s^{-1}$	A_t, deg	n_t	$\omega_t, rad \cdot s^{-1}$	A_t, deg
8	0.614	3.583	8	0.614	3.583
16	1.227	2.289	15	1.150	2.430
24	1.841	1.445	25	1.917	1.370
32	2.454	0.967	31	2.378	1.013

Table 1 lists the target signal properties, where n_t denotes the number of periods of the respective sinusoid contained within the measurement time, and $\omega_t = 2\pi n_t / T_m$ the corresponding frequency. The signals were obtained by inserting these properties in:

$$f_t(t) = \sum_{k=1}^{N_t} A_t(k) \sin(\omega_t(k) t) \tag{1}$$

Target signal amplitudes $A_t(k)$ were scaled using the low-pass filter of (Zaal et al., 2009):

$$A_t(k) = \left| \frac{(1 + T_A j\omega_t(k))^2}{(1 + T_B j\omega_t(k))^2} \right|, \tag{2}$$

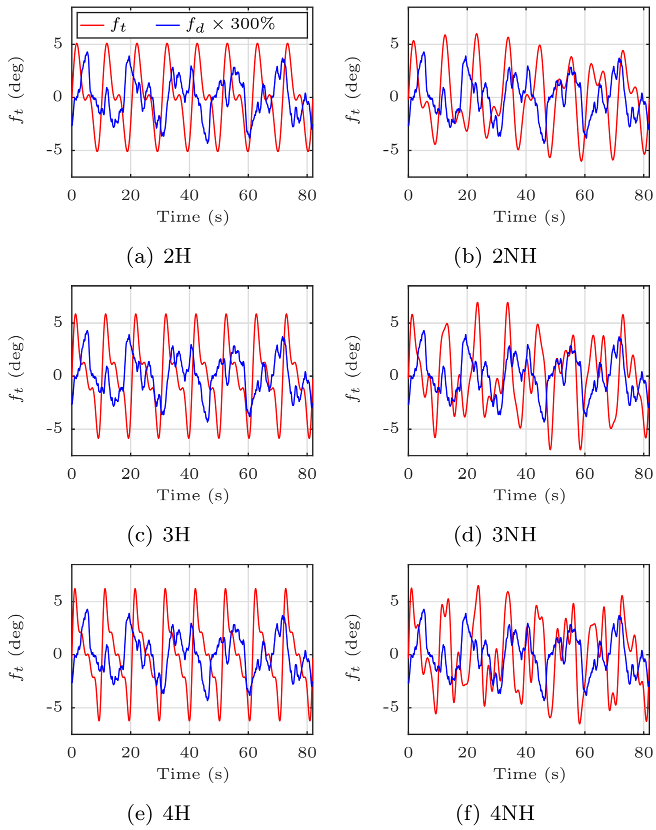
with $T_A = 0.1$ s and $T_B = 0.8$ s.

For the non-harmonic signals, the non-harmonic wave was chosen to be the first lower integer of the frequency used for the harmonic targets. Only in the case of $n_t = 24$ the non-harmonic was chosen to be n_t =25 since n_t =23 would be a frequency also present in the disturbance signal (Table 2).

The six resulting harmonic and non-harmonic signals are shown in Figure 2, together with the disturbance signal f_d which remained the same during all conditions. The disturbance signal was added to allow for the multiloop identification required in tasks with expected feedforward-feedback HC dynamics (Drop et al., 2013). It is the same as used in (Zaal et al., 2009) and is presented in Table 2.

Table 2. Disturbance signal properties.

Disturbance, f_d			
n_d	$\omega_d, rad \cdot s^{-1}$	A_d, deg	ϕ_d, rad
5	0.383	0.6714	-0.269
11	0.844	0.5077	4.016
23	1.764	0.2531	-0.806
37	2.838	0.1290	4.938
51	3.912	0.0784	5.442
71	5.446	0.0476	2.274
101	7.747	0.0298	1.636
137	10.508	0.0216	2.973
171	13.116	0.0180	3.429
226	17.334	0.0152	3.486



(a) 2H (b) 2NH (c) 3H (d) 3NH (e) 4H (f) 4NH

Fig. 2. Target signal f_t, different in all six conditions; the disturbance signal f_d remains the same.

3. HC MODEL AND SIMULATIONS

3.1 HC model

An aircraft pitch angle tracking task with a pursuit display, illustrated in Figure 3, will be studied. For the sake of performing multiloop system identification of the HC dynamics, the tracking task is implemented as a combined target-tracking, disturbance rejection task, see Figure 4.

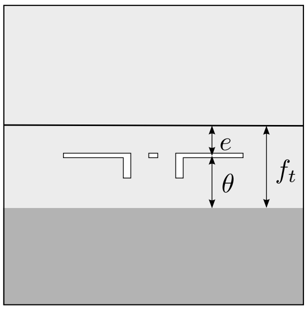


Fig. 3. Pursuit display for aircraft pitch control (neither past nor preview information is presented).

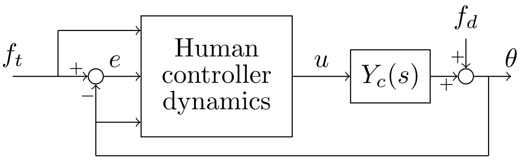


Fig. 4. Control scheme studied here. The HC perceives the target signal f_t, the perturbed system output θ and the error e from a pursuit display and generates control signal u. Y_c are the controlled element dynamics, with s the Laplace operator.

With a pursuit display, f_t is directly available, and the HC can apply a feedforward control strategy to improve performance. An 'ideal' feedforward controller inverts the controlled element dynamics (Wasicko et al., 1966):

$$\frac{u(s)}{f_t(s)} = \frac{1}{Y_c(s)} \Rightarrow u(s) = \frac{1}{Y_c(s)} \cdot f_t(s) \tag{3}$$

The system output is then found to be (with $f_d = 0$):

$$\theta(s) = Y_c(s) \cdot u(s) = Y_c(s) \cdot \frac{1}{Y_c(s)} \cdot f_t(s) = f_t(s) \tag{4}$$

Due to HC limitations in perception and actuation, such as processing time delays and neuromuscular dynamics, the perfect feedforward is rarely possible. In addition, because of the unpredictable disturbance signal f_d, in the task at hand the HC will need a feedback path. Hence, the HC model studied here will be a combination of a feedforward and feedback controller, as illustrated in Figure 5.

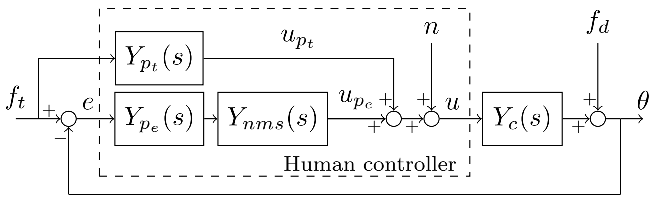


Fig. 5. HC model block diagram.

The feedforward path Y_{p_t} is modeled according to the *Inverse Feedforward Model* of (Laurense et al., 2015):

$$Y_{p_t}(s) = K_{p_t} \frac{1}{Y_c(s)} \frac{1}{(T_I s + 1)^2} e^{-s\tau_{p_t}}, \tag{5}$$

with K_{p_t} the gain, T_I the lag time and τ_{p_t} the time delay of the feedforward. The feedback path Y_{p_e} is described as:

$$Y_{p_e}(s) = K_{p_e}(T_L s + 1) e^{-s\tau_{p_e}}, \tag{6}$$

where K_{p_e} is the feedback gain, T_L is the lead time and τ_{p_e} is the feedback path time delay, assuming that the CE dynamics are second-order (McRuer and Jex, 1967). The feedforward and feedback delays are possibly different, because the HC might be able to anticipate the future course of the target. The neuromuscular system (NMS) is described by:

$$Y_{nms}(s) = \frac{\omega_{nms}^2}{s^2 + 2\zeta_{nms}\omega_{nms}s + \omega_{nms}^2}, \tag{7}$$

with ω_{nms} and ζ_{nms} the natural frequency and damping, respectively (McRuer et al., 1968).

3.2 HC Model Simulations

Preliminary computer simulations were performed using the HC model defined above, with parameter values as estimated in (Laurense et al., 2015), see Table 3.

Table 3. HC Parameters used for simulations.

K_{p_t}	T_I	τ_{p_t}	K_{p_e}	T_L	τ_{p_e}	ω_{nms}	ζ_{nms}
-	s	s	-	s	s	rad/s	-
1	0.28	0.2	1.3	0.4	0.28	10.5	0.35

The HC model tracking performance, expressed in Root-Mean-Square (RMS) of the error signal e ($=f_t - \theta$), for the six target signal definitions introduced in Section 2 is shown in Figure 6. Note that the scores for the non-harmonic signals are shown slightly to the right, to better distinguish them from the scores with harmonic targets.

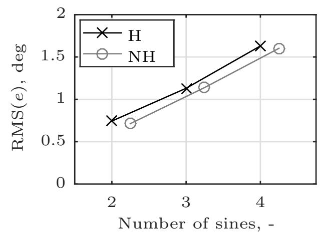


Fig. 6. Simulated score parameter for all conditions.

The computer simulations show that when using the fixed HC model, no differences in tracking performance are found between the harmonic and non-harmonic targets. Tracking performance decreases when the number of sinusoid components increases from 2 to 4, illustrating that the signal's (higher) frequency content does matter. Clearly, the fixed feedforward HC model is *not* able to take the predictability of a target signal into account.

4. EXPERIMENT

4.1 Control Task

Subjects performed an aircraft pitch attitude target tracking and disturbance rejection task, with a pursuit display. CE dynamics were defined as:

$$Y_c(s) = \frac{K_c \omega_b}{s(s + \omega_b)}, \tag{8}$$

with $K_c = 2.75$ and $\omega_b = 2$. Only one disturbance signal f_d was used; the target signal f_t was varied. The disturbance and target signals were as defined in Section 2.2.

4.2 Apparatus

The tracking task was presented on a central visual display in a pursuit configuration, see Figure 3. The ViewPixx Lite Visual Stimulus Display had an update rate of 120 Hz; the image generation delay was around 15-20 ms. The distance to the subject's eyes was 90 cm. A display gain of 16 pixels per degree of pitch was used. For the experiment there were no outside visuals or motion cues.

The fore/aft axis of an electronically-actuated side-stick was used to give control inputs, u; the lateral axis was fixed. The stick had no break-out force, a maximum deflection of $\pm$ 17 deg. Its stiffness was set to 1.0 N/deg over the complete deflection range; its inertia were set to 0.01 kg·m^2 and the damping coefficient was 0.2.

4.3 Experiment Setup and Procedure

The experiment had one independent variable, namely the six target signals defined in Section 2.2. The resulting six conditions were ordered through a Latin square. A subject first completed one run of each condition for familiarization. After this run the subject was asked to give a subjective rating for the predictability of the signal, using the direct magnitude estimation method of (Meyer, 1971). This rating was asked again when the experiment was completed. After each run the tracking score, expressed as RMS(e), was shown.

Subjects performed several runs of 90 seconds per condition. When the subject achieved a stable performance, five measurement runs were done. From each of these runs, only the last 81.92 seconds were used as measurement data.

4.4 Subjects and Instructions

Six subjects performed the experiment, 5 males and 1 female, between the age of 26 and 30 years (average age 28). All were experienced in tracking tasks. Instructions were to minimize the tracking score RMS(e).

4.5 HC Model Identification

The HC model defined in Section 3 was fit to the experimental data using the parameter estimation method of (Zaal et al., 2009).

4.6 Dependent Measures

To assess tracking performance and control activity, the RMS values of the error and control signals, respectively, were used. To assess the subjective predictability of the target signal, the pre- and post-experimental ratings using the Meyer scale were used (Meyer, 1971).

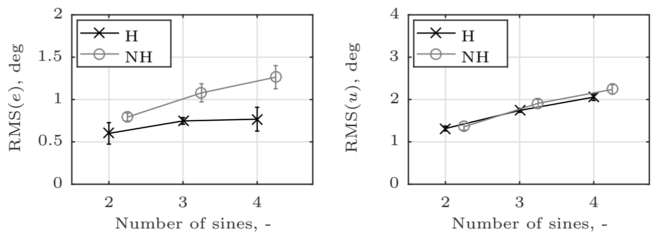
4.7 Hypotheses

We expected that the predictability of the target signal would range between conditions 2H (high) and 4NH (low). Hence, our first hypothesis (H. I) was to see a change in HC control behavior from a combined feedforward and feedback strategy (2H) to a purely feedback control strategy (4NH). Our second hypothesis (H. II) was to see a better tracking performance for the harmonic conditions as compared to their non-harmonic equivalents. This is more in line with common sense and previous investigations, but in contrast to what we found for the computer simulations.

5. RESULTS AND DISCUSSION

5.1 Tracking performance and control activity

Figure 7 shows that subjects scored better with the harmonic signals as compared to their non-harmonic counterparts (left), with a slightly lower control activity (right). As hypothesized (H. II), subjects were able to use the predictable aspect in the harmonic signals to improve their score. This in contrast to the computer simulations, which used the same HC model to obtain the model predictions. Clearly, our subjects learned from, and adapted to, the more predictable harmonic target signals, which repeated themselves eight times in every measurement run. Performance decreases and control activity increases when more sine components are added, but lesser so for the more predictable, harmonic signals. In fact, performance was better in the 4H condition then in the 3NH condition.



(a) Performance (b) Control activity

Fig. 7. Tracking performance and control activity.

5.2 HC Model Fit

Figure 8 shows estimates of six HC parameters. The feedforward gain K_{p_t} is nonzero in all conditions, and is considerably higher for the harmonic signals, Figure 8(a). It decreases slightly when more sine components are added, reducing the feedforward activity. The feedforward time lag T_I was extremely small for all conditions, Figure 8(d), indicating that subjects hardly 'filtered' the target internally. Figure 8(e) shows estimates of the feedforward time delay τ_{p_t}. For the harmonic signals, the delay goes to the lower boundary of the estimation, set to zero seconds, which clearly indicates that our subjects were perfectly capable of anticipating the target. For the non-harmonic signals, time delays were in the order of 250 - 350 ms, typical for tracking tasks with unpredictable quasi-random target signals (McRuer and Jex, 1967).

Subjects also had a slightly higher feedback gain K_{p_e} for the harmonic signals, Figure 8(b); it decreases when more sinusoid components are added. The lead time constant T_L approximates the 'ideal' value of 0.5 seconds (for the CE dynamics of Eq. (8)) for the 2H condition, but increases when more components are added. The lead is always higher for the non-harmonic signals, indicating that subjects had to work harder to obtain the same stability margins. The time delay, Figure 8(f), was approximately

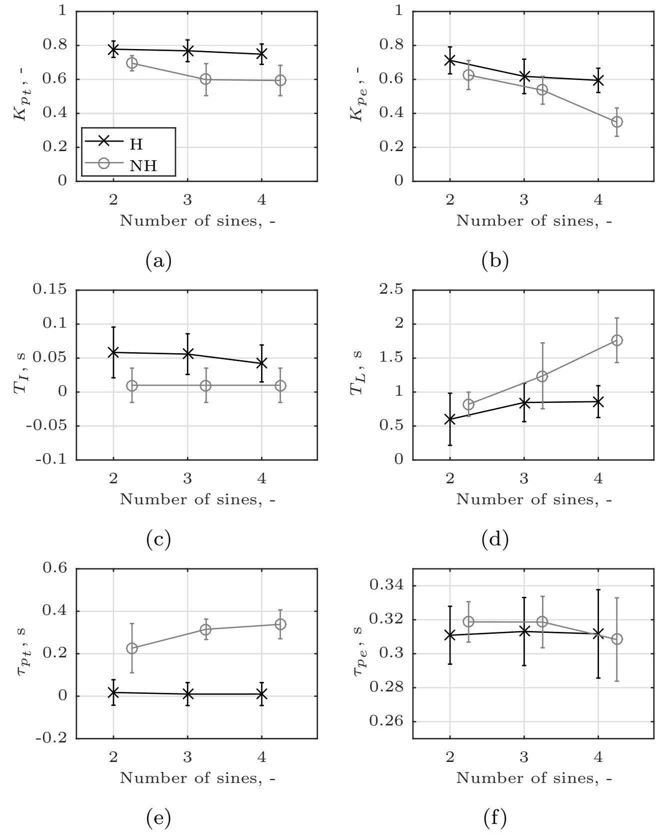


Fig. 8. Estimated HC model parameters.

the same for all conditions, between 300 and 320 ms, very similar as found in (McRuer and Jex, 1967).

Recall that Hypothesis I expected a change from combined feedback and feedforward in the 2H condition, to a purely feedback control strategy in the 4NH condition. Clearly, this was not the case as in all six conditions the feedforward path was activated, albeit with smaller gains for the non-harmonic targets. Hypothesis I is therefore rejected.

5.3 Magnitude Estimation

Figures 9(a) and 9(b) show the magnitude estimation results before and after the experiment, respectively. Generally speaking, we see that subjects became better in marking the difference in predictability between the experimental conditions. As expected, the harmonic signals were stated to be more predictable as compared to the non-harmonic signals. Whereas for the latter predictability decreases when more sinusoid components are added, this seems not to be true for the harmonic signals.

6. CONCLUSIONS

We investigated the predictability of a target signal as a function of the number of sine components, and whether the components were harmonics or not. A combined target-tracking disturbance rejection experiment was done, with a pursuit display. For all conditions, including those with up to 4 non-harmonic sinusoid components, the feedforward path was active. The harmonic signals led to better performance, lower control activity, the highest

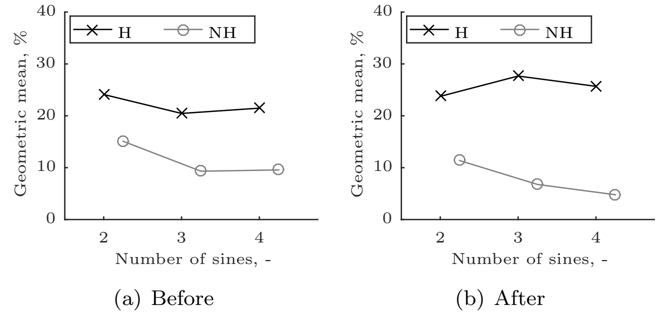


Fig. 9. Results of the magnitude estimation.

feedforward gains, and close to zero feedforward time delays. Subjective ratings of the signal predictability support the objective findings. Future work focuses on investigating how other signal properties affect predictability, and the subsequent effect on the feedforward component.

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