Engineering modelling in transfer function form for diverse learners

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Abstract: Traditionally, the modelling of real systems in engineering, using transfer functions, has been done in a mathematically intense manner. However, non-traditional learners such as mature students, part-time students and students without a conventional second-level educational background may not have strong mathematical foundations; in addition, all students increasingly expect technical work which is practical and which motivates independent learning. This paper reports on, reflects on and evaluates an innovative experiment developed by the author to estimate a transfer function model of a persons’ eye-brain-hand motor response. In the experiment, carried out using a PC with data acquisition capability, the person is successively asked to track, with a mouse, ten sine wave signals at different frequencies on a computer screen. Based on an average of the data recorded, the persons eye-brain-hand motor response in the frequency domain is recorded (and may be summarised on a *Bode plot*). Subsequently, the parameters of a single input, single output (SISO) process model may be determined, using the analytical technique developed by O’Dwyer (2002).

1. Introduction

Significant effort has been devoted to determining a model for the human operator in a simple closed loop system. Early work was performed by Bates (1947) and Tustin (1947); the non-linear nature of the model required was recognised. Graebe *et al.* (1961) report that, to model the human tracking response, “it has become customary to treat the problem with some linear time invariant approximate transfer function that will help account for at least some of the empirical facts”. The authors suggest the following transfer function model:

$$G_m(s) = \frac{K_m(1+T_{m1}s)e^{-s\tau_m}}{(1+T_{m2}s)(1+T_{m3}s)},$$

with τ_m being the reaction time delay, $\tau_m \in [0.2,0.5]$ seconds; $T_{m1} \in [0.25,2.5]$ seconds; T_{m2} is the neuromuscular lag for the arm, $T_{m2} \in [0.1,0.16]$ seconds; $T_{m3} \in [5,20]$ seconds; K_m is the (variable) model gain. Such a model was also developed by Alexík (2000). Extensive work on modelling of neurological control systems is presented by Stark (1968); in elegant experiments, the author determines, for example, frequency response plots for the dynamic characteristics of the human motor co-ordination system and frequency response plots of the control system of the human hand. In other work in the frequency domain, Gittleman *et al.* (1992) developed transfer functions for human tracking response based on a one-dimensional, sine wave tracking experiment. A joystick is used to allow tracking of the sine wave. The model transfer function developed is second order, with one zero, and a time delay. The authors quote representative values of the model gain as being from 1 to 100; representative values for the two model poles are from 0 to 20s and $0.1s \pm 20\%$, respectively; the representative value for the model zero is from 0 to

2.5s; the representative model time delay is $0.2\text{s} \pm 20\%$. In another contribution, Hess (1996) suggests that a human in a control loop may be modelled as either an integrator plus time delay model or a third order model with one pole, one zero and a time delay. If the human is modelled as an integrator plus time delay model, the author suggests that the equivalent time delay is approximately 0.27s, with the equivalent time delay being equal to approximately 0.15s when the human is modelled in third order plus delay form.

The origin of the individual terms of the model in the physiological and psychological condition of the human operator has also been mooted. For example, Hess (1996) suggests that the time delay represents the cumulative effect of actual time delays in the human information processing system (e.g. visual detection times, neural conduction times), the low frequency effects of higher frequency human operator dynamics (e.g. muscle actuation dynamics) and higher frequency dynamics in the controlled element itself. In another example, Boer and Kenyon (1998) state that delay time in a human operator is primarily a result of transport delays and central nervous system latencies. The authors also state that, depending on the input bandwidth, the delay may include neuromuscular lag and a time varying component that depends on factors such as attention level and task difficulty.

In a wider discussion of the measurement of sensory-motor control performance capacities, Jones (1995) suggests that the use of sinusoidal tracking signals is valuable for the study of the human frequency response; in particular, the "periodicity, constantcy of task complexity (over cycles) and spectral purity of sine targets" are useful for detecting changes in performance (such as learning or lapses in concentration) within an experimental run. A number of references are quoted.

The experimental work reported in this paper has been inspired primarily by the work of Stark (1968) and Gittleman *et al*. (1992). As an alternative to the use of a joystick by Gittleman *et al*. (1992), it has been decided to track sine waves, at different frequencies, on a computer screen using the PC mouse. The subsequent transfer function models, deduced from the frequency response data, have been developed using an analytical method, as proposed by O'Dwyer (2002). The analytical method is based on direct calculation of the parameters from the frequency response, using simultaneous equations.

2. Experimental details

The experiment is carried out using a personal computer with a data acquisition card and suitable software (MATLAB/SIMULINK and HUMUSOFT) to record the input sine wave (generated in SIMULINK) and the persons' tracking sinewave. The implementation in SIMULINK is shown in Figure 1.

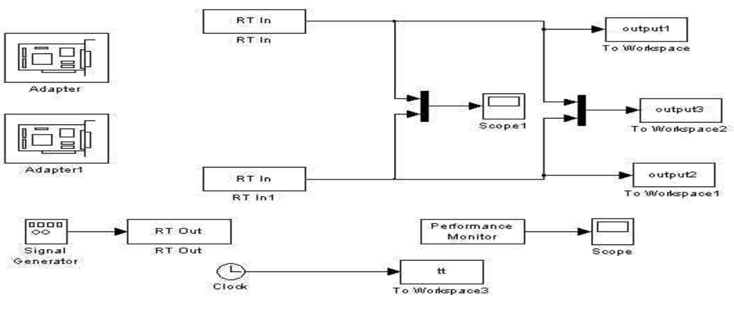

Figure 1: SIMULINK implementation

The person is requested to track, with a mouse, ten sine wave signals at frequencies from 0.1 hZ to 1 hZ, in steps of 0.1 hZ, on a computer screen. Six cycles of the sine wave are tracked at any one frequency. A typical example of one sine wave input signal (at a frequency of 0.1 hZ), and a person's tracking attempt, is shown in Figure 2. As expected, subjects tended to have little difficulty in tracking such slow signals; as the frequency of the input signal increased, tracking difficulties also increased.

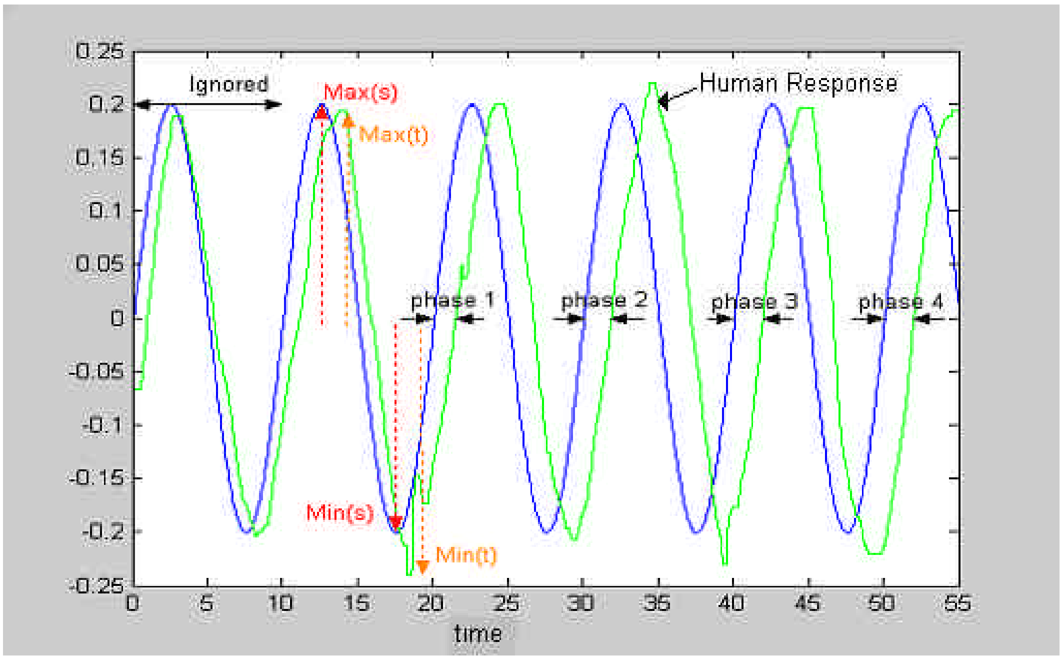

Figure 2: Typical tracking attempt

The magnitude (i.e. the ratio of the amplitude of the output and input signals) and the phase difference between the output and input signals (labelled as phase 1, phase 2 etc. on Figure 2), were recorded at the ten individual frequencies. Based on an average of the magnitudes and phase differences recorded, a *Bode plot* is drawn from the data, and a transfer function for the motor response is developed from the plotted data. Specifically, the amplitude is taken over an average of four cycles, ignoring data from the first and last cycle. The phase is taken as the average of the four phases indicated in Figure 2; again, the early recorded data is ignored. Such early data tends to be less reliable, as experience had shown that the user needs a short time to adjust to the frequency of the input signal.

3. Experimental results

A series of experimental results have been collated. Altogether, since the programme was developed, seventy-six sets of data have been gathered. Some of these sets of data have had to be excluded from the analysis, as, despite instructions to track the data after it becomes visible on the screen, in some cases subjects predicted the very regular sine wave input. Further work is required on the algorithm to minimise this problem.

After the data mentioned above was excluded, 54 data sets remained. Data was gathered when tracking was done with both the dominant and non-dominant hand. The data gathered can be classified as follows:

1. Data gathered in May 1999 from a 36 year old male (myself). Three sets of data was gathered for the dominant hand and two sets of data was gathered for the non-dominant hand.
2. Data gathered in January 2006, in the early morning and late evening, from a 42 year old male (myself). Fourteen sets of data was gathered for the dominant hand and thirteen sets of data was gathered for the non-dominant hand.
3. Data gathered from May 1999 to January 2006 from both male and female students, with a typical age of 21 years. Twenty sets of data was gathered for the dominant hand and six sets of data was gathered for the non-dominant hand.
4. Data gathered in May 1999 from an older group of subjects. This is non-dominant hand data.

Figure 3 shows the Bode plot of all the data gathered. Magnitude is measured in decibels (dB) with phase measured in degrees. Table 1 gives the average data, at angular frequency ω (phase ϕ_p is measured in radians and magnitude $|G_p|$ is recorded in non-decibel format).

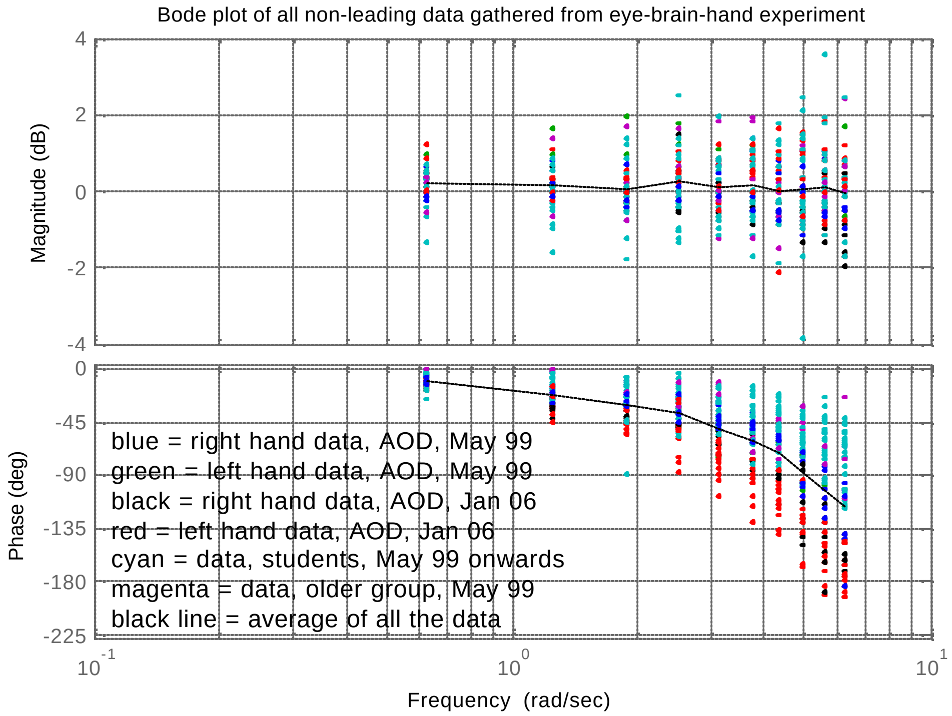

Figure 3: Bode plot of all the data gathered

ω (rads/s)	0.68	1.30	1.90	2.56	3.14	3.81	4.33	5.03	5.70	6.28
ϕ_p (rads)	-0.20	-0.39	-0.55	-0.66	-0.87	-1.08	-1.25	-1.55	-1.82	-2.03
$\lvert G_p \rvert$	1.02	1.01	1.00	1.02	1.01	1.01	1.00	1.01	1.01	0.99

Table 1: Average of the data

It should be noted that the resolution possible on the phase varies with frequency, as the sample time of 0.05 seconds used to gather the data is the minimum possible with the data acquisition card and software used. The resolution on the phase is 0.031 radians at $\omega = 0.68$ rads/s, rising linearly to 0.314 radians at $\omega = 6.28$ rads/s. As phase varies almost linearly with frequency, the resolution in phase as a percentage of the phase recorded is approximately constant at 16%.

On application of the analytical method of transfer function determination (O'Dwyer, 2002), it was discovered that, on average, that the data could be modelled by a gain term, K_m (which depends on the magnitude), and a reaction time delay term, τ_m (which depends on the phase). In addition, as Table 1 reveals, K_m is approximately 1, even at higher frequencies. This means that subjects tend to be able to track the amplitude of the sine wave accurately. Thus, overall, the data may be summarised by a delay term, which may be determined as 0.30 seconds. After adjusting for the sample time of 0.05 seconds, the average eye-brain-hand motor response reaction time is recorded as 0.25 seconds.

Table 2 summarises results obtained from a more detailed analysis of the data. The delay determined could be expected to have a maximum inaccuracy of 16%.

Condition	*Delay determined*
Average of all data gathered	0.25 s
Average, dominant hand data, male/female students, May 1999 – Jan. 2006	0.14 s
Average, dominant hand data, 22 year old male (William), May 1999	0.16 s
Average, dominant hand data, 36 year old male (myself), May 1999	0.20 s
Average, dominant hand data, 42 year old male (myself), January 2006	0.32 s
Average, non-dominant hand data, 22 year old male (William), May 1999	0.19 s
Average, non-dominant hand data, male/female students, May 99 – Jan. 06	0.20 s
Average, non-dominant hand data, 42 year old male (myself), January 2006	0.41 s

Table 2: Summary of results obtained

Clearly, the delay recorded, on average, increases with age; on average, there is also an increase in reaction time required if the non-dominant hand is used. Both of these results are intuitively expected.

Other results showed that there were no significant differences in reaction times recorded when

- Data was gathered in the morning (07:55-12:11) versus data being gathered in the late evening (20:00-21:20)
- Data was gathered from male and female students and compared.

4. Pedagogical issues

Since its development in 1999, this experiment has been carried out by students taking a control engineering option in the programmes in electrical/electronic engineering at DIT. Traditionally, the modelling of real systems in engineering, using transfer functions, has been done in a mathematically intense manner. However, non-traditional learners such as mature students, part-time students and students without a conventional second-level educational background may not have strong mathematical foundations; in addition, all students increasingly expect technical work which is practical and which motivates independent learning. The author has found that students are enthusiastic about the experiment and frequently spend over the allocated time on aspects of it.

The following questionnaire was distributed to a group of students performing the experiment in the 2005-6 academic year, to get formal feedback on their experiences with the experiment.

Please answer the following questions. To answer each question, please write a number between 1 and 5, with

5 - strongly agree
4 – agree
3 – unsure
2 – disagree
1 – strongly disagree

1. *The work was a beneficial learning experience (compared to other exercises)*
2. *The work is user-friendly*
3. *The work complements and enhances my understanding of lecture material*
4. *The work is fun and sustained my interest*
5. *I became more interested in the material because of this work*
6. *There is enough time to perform the work*
7. *I would recommend this work to others*
8. *Any other comments*

When the feedback was analysed, students agreed with the statements that:

- *The work was a beneficial learning experience (compared to other exercises)* – average number: 4.3
- *The work is user-friendly* – average number: 4.2
- *The work complements and enhances my understanding of lecture material* – average number: 4.5
- *The work is fun and sustained my interest* – average number: 4.5
- *I became more interested in the material because of this work* – average number: 4.0
- *I would recommend this work to others* – average number: 4.3

Students were unsure about the statement that *There is enough time to perform the work* (average number: 3.0).

Overall, student feedback is encouraging; the reasons for this, in the authors opinion, are

- The experiment provides direct feedback to the user on the PC screen
- The experiment is not excessively time-consuming; a typical experiment time to gather one set of data, at 10 frequencies, is 10 minutes
- A competitive edge among (typically, male) students is frequently observed, with a desire to have the shortest reaction time
- A motivational aspect for some students is the application of the idea in biomedical engineering, possibly in the diagnosis of some motor response disorders; as the experiment provides direct feedback to the user on the PC screen, it lends itself to providing motivation to a person attempting to regain motor function after a neurological setback, such as a stroke.

However, the experiment is somewhat tedious to carry out because of its repetitive nature. In addition, as mentioned, it is possible for subjects to predict, rather than track, the very regular sine wave inputs.

5. Conclusions and Future Work

The paper reports on the estimation of a simple transfer function model of a persons' eye-brain-hand motor response, using an innovative experiment. The data from the experiment may be analysed by the students to determine the transfer function model (for those students with the required mathematical foundations). Alternatively, for students without such foundations, the data may be imported into a programme written by the author in MATLAB and the transfer function model results. The experiment is practical, though somewhat tedious to carry out. For future work, the use of a less predictable alternative to the sine wave signal would be desirable.

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