REACTOR OPERATOR-IN-THE-LOOP DYNAMIC MODELLING

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ABSTRACT

The description of human operator dynamic characteristics in mathematical terms compatible with control engineering practice is an essential prerequisite to the analytical treatment of manual reactor control systems. Safe reactor operation requires effective operator control through interaction with plant dynamics, manipulators and displays. Traditional static analysis methods consider only specific situations; they fail to adequately explain the mutual interactions between the operator and the reactor plant characteristics. In this paper we investigate the theory for describing operator-reactor characteristics based on the methods of conventional control engineering techniques. The primary purpose of the experiments reported is the validation of the quasi-linear operator model.

Key Words: pyrofusion neutron source dynamics, frequency response, state-space, MATLAB/Simulink

1 INTRODUCTION

The highly adaptive nature of the human operator makes a mathematical description difficult to obtain; however quasi-linear model with parameters that vary with the system task variables has been successfully applied to many human-vehicle situations [1]. The operator-reactor dynamic models under development may be used for:

1. Analysis of the overall effectiveness of operator training programmes and quantitatively assess an individual operator's progression and understanding of the plant dynamics.

2. Estimation of overall operator-reactor system dynamic response, stability and average performance.

3. Determination of controllable reactor dynamics and manual controllability boundaries.

4. Indication of the type of additional system equalization (to be achieved via displays, manipulators (control rods), or by reactor modifications) desirable to achieve better operator control - including the effects on the operator characteristics of such modifications.

5. Identification of the maximum forcing function bandwidth compatible with reasonable control.

2 HUMAN CONTROLLER

There are three task variables that have a major effect on the operator's dynamics - the forcing function characteristics (reactivity perturbation), the controlled-element (reactor and display) dynamics, and the manipulator control rod drive mechanism and load as indicated in Fig.1. Operators in manual control systems exhibit a type of behaviour which is analogous to the behaviour which is analogous to the behaviour of equalising elements inserted into a servo-system to improve over-all dynamic performance [2].

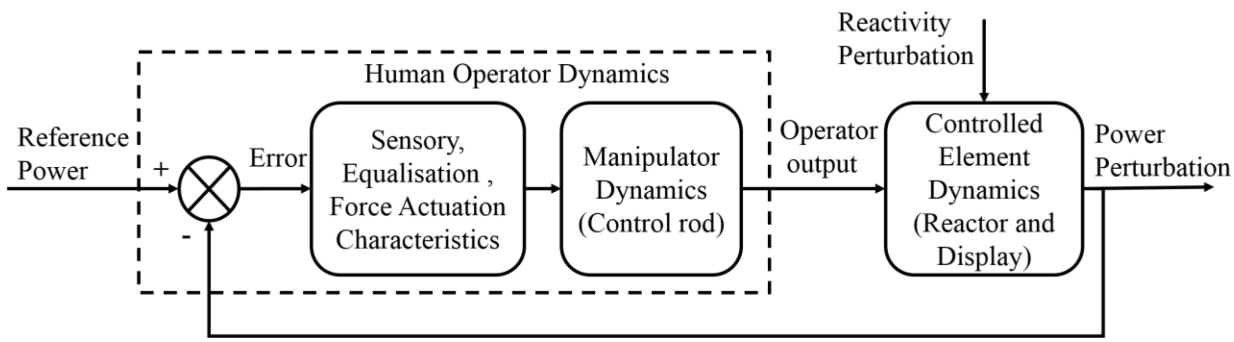

Figure 1. Operator-reactor system.

Quasi-linear systems are appropriate engineering mathematical descriptions for the types of non-linear and time-varying behaviours that are exhibited by humans acting as control elements. Describing function analysis is the approximation of the non-linear system by a linear time-invariant transfer function that depends on the amplitude of the input waveform plus a non-linear element. The analytical-verbal model has previously been used for human compensatory tracking; the low frequency approximation of the describing function is given by Eqn. 1 [1]:

$$Y_p = \frac{K_p e^{-j\omega\tau}(T_L j\omega+1)}{(T_I j\omega+1)(T_N j\omega+1)} \quad (1)$$

1. $(T_N j\ \omega + 1)^{-1}$ is a first order neuromuscular lag term which is partially adjustable for the task.

2. The pure delay term $e^{-j\omega\tau}$ is due to sensor (retina) excitation, nerve conduction, computational lags, and other data processing activities in the central nervous system; it is taken to be a constant as it has been proven to be essentially invariant with forcing function and controlled element dynamics [3].

3. The equalising characteristics, $\frac{T_L j\omega+1}{T_I j\omega+1}$ coupled with the gain K_P are the major elements in the adaptive capability of the human which allow the control of different dynamic devices. Adaptation is the selection by the operator of a specific form (lag-lead, lead-lag, pure lead, pure lag or pure gain) for the equalisation characteristics. Optimization is the adjustment of the parameters of the selected form to satisfy some internally generated criteria. The operator aims to select a form that is compatible with good low frequency, closed-loop response and the absolute stability of the system.

3 CONTROLLED ELEMENT

The controlled element for this study is the VR-1 Training Reactor at the Czech Technical University in Prague. The VR-1 reactor is a pool-type light-water reactor based on low enriched uranium with maximum thermal power of 1 kW. The moderator is light demineralised water which is also used as a reflector, a biological shielding and a coolant. Heat is removed from the core by natural convection [4]. A linear point reactor model captures the dominant dynamics of this controlled element and the appropriate zero-power transfer function is given by Eqn.2:

$$Y_c(s) = \frac{\delta n}{\delta \rho} = \frac{n_0(s+\lambda)}{\Lambda s\left(s+\frac{\beta}{\Lambda}\right)} \tag{2}$$

The controlled element model contains parameter values for delayed neutron fraction, n_0 neutron generation time,Λ and decay rate of neutron precursors, λ. In this approximation we have taken the initial reactivity to be zero, corresponding to equilibrium operation at an arbitrary power level.

4 FREQUENCY RESPONSE

To satisfy tracking requirements and rejection of low frequency disturbance it is preferable for the system's open-loop transfer function to have large gain at low frequencies; while at high frequencies the gain would be kept low to filter out high frequency noise. For a unity feedback system of the type shown in Fig. 2 the desired closed-loop transfer function is that of a low-pass filter. The region near the crossover frequency ω_c where $|Y_p Y_c| = 1$ is of most importance. The operator's describing function, $Y_p(j\omega)$, must be adjusted so that ω_c, exceeds the highest important frequency in the input, ω_i. The shape of $Y_p Y_c$ at near crossover frequency determines the dynamics of the dominant modes of system response. For good feedback control, neutrally stable or unstable dominant modes should be avoided by adjusting the system so that there is a positive gain margin as given by Eqn. 3

$$|Y_p Y_c| < 1 \text{ when } \measuredangle Y_p Y_c = -\pi \tag{3}$$

and a positive phase margin as given by Eqn. 4.

$$\measuredangle Y_p Y_c > -\pi \text{ when } |Y_p Y_c| = 1 \tag{4}$$

The operator is expected to adjust his describing function so that the open-loop function $Y_p Y_c$ in the vicinity of the gain crossover frequency ω_c, is closely approximated by Eqn.5.

$$Y_p Y_c = \frac{\omega_c e^{-j\omega\tau}}{j\omega} \tag{5}$$

5 NON-LINEAR MODEL

The controlled element as described by Eqn. 2 may exhibit conditional stability for particular inputs and therefore is difficult to control. This may result in non-linear controller action which can be decomposed into three interconnected elements as indicated by the block diagram shown in Fig. 2. The delay at the operator's input is represented by a constant value transport delay. The linear dynamics are represented by the describing function given in Eqn. 1. The output non-linearity is a static piecewise linear function parametrized by breakpoint locations that map the output of the linear block to the operator's output (rod movement).

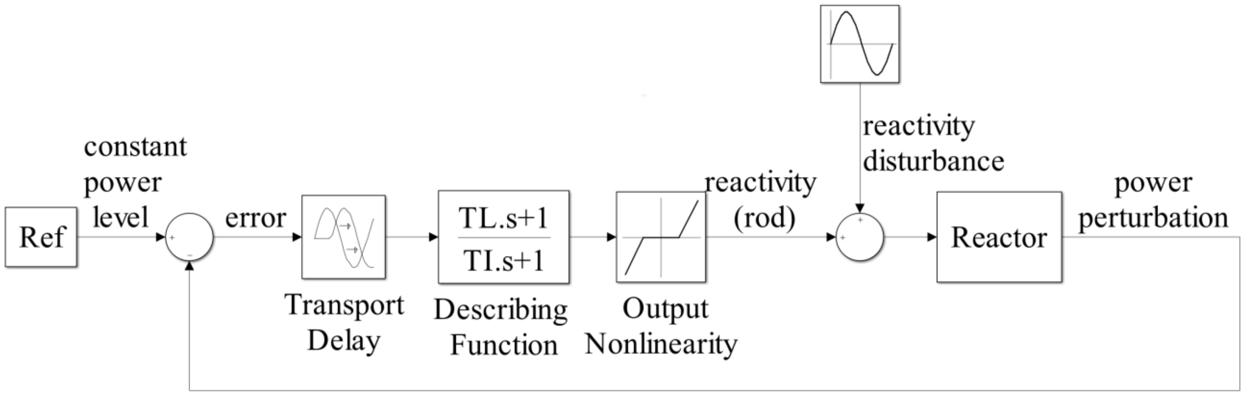

Figure 2. Non-linear Wiener model of the operator-reactor system.

6 EXPERIMENT TECHNIQUES

Previous knowledge of human operator behaviour has been focused on pilot-vehicle characteristics in compensatory tracking using data from simulators. As we are utilising live reactor data to analyse operator behaviour we are constrained, at least in this initial investigation, to the study of reactivity disturbance rejection tasks. The reported experiments were performed at the VR-1 reactor. The operator responds to a visual stimulus of the reactor power displayed on the monitor indicated in Fig. 3. The operator manipulated one of the control rods using the buttons indicated in the figure. The three selected subjects were skilled operators of the VR-1 reactor - through this choice of individuals the intent was to reduce the effects of population inhomogeneities on the data.

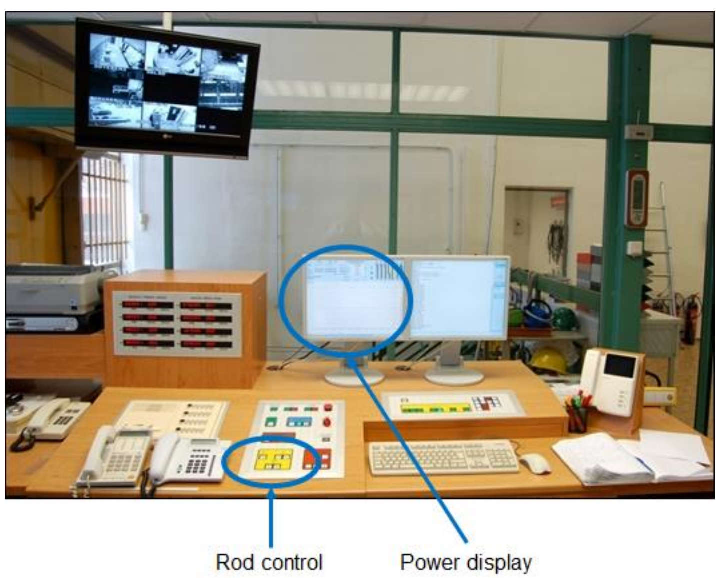

Figure 3. Operator control desk [4].

The test situation involved the operator manipulating the control rod position to reject a power disturbance caused by the movement of a device known as the HOPIK. The HOPIK device was programmed to input a low frequency periodic square wave forcing function, which by its nature is composed of sinusoids at different frequencies and can be split into separate 'step' changes. The operators are instructed to minimize the error as the power changes from a steady-state level. The reactor power (controlled element output/ operator visual stimulus input) and the rod position (operator output) signals are recorded at a sampling rate of 0.1 seconds; Fig.4 shows an example of the data collected for one of the subjects. The data for each experiment was de-trended to remove physical-equilibrium offsets measured prior to the excitation input signal.

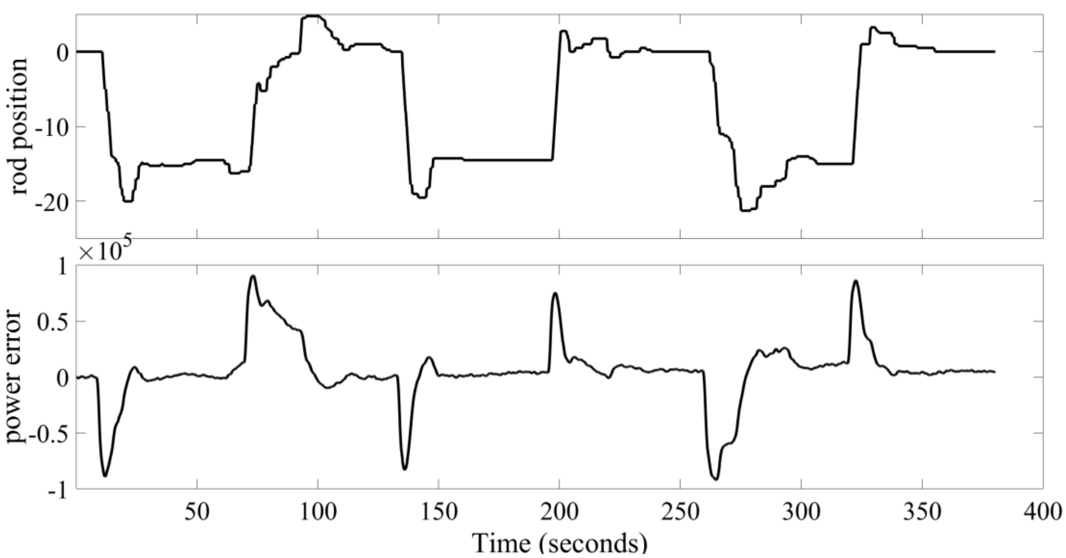

Figure 4. Example test data for one operator.

7 MODEL ESTIMATION

The computer aided control system design software package MATLAB was used to process, estimate and analyse the data for the three subjects and six experiments. A non-linear Hammerstein model structure was fit to a total of eighteen datasets (six experiments for each of the three subjects). Fig.5 shows the result of each estimation. The fit percent metric is the root mean squared error measure of how well the response of the model fits the estimation data, expressed as a percentage. The chosen non-linear model structure showed a reasonably good fit to over 94 percent of the experiments. Seventeen of the eighteen estimations had a fit at 90 percent or above; the worst fit experiment was 89.56 percent.

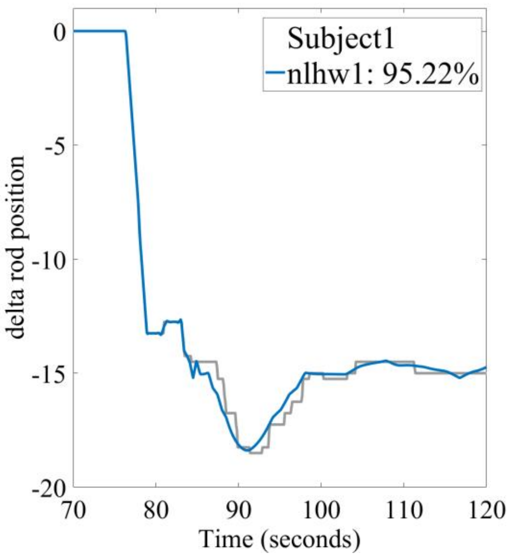

Figure 5. Example of non-linear estimated model simulation.

8 INTERPRETATION OF DATA

In order to investigate the variability of the operator's describing functions we may examine the frequency responses for all 6 experiments for the three operators shown in Fig.6.

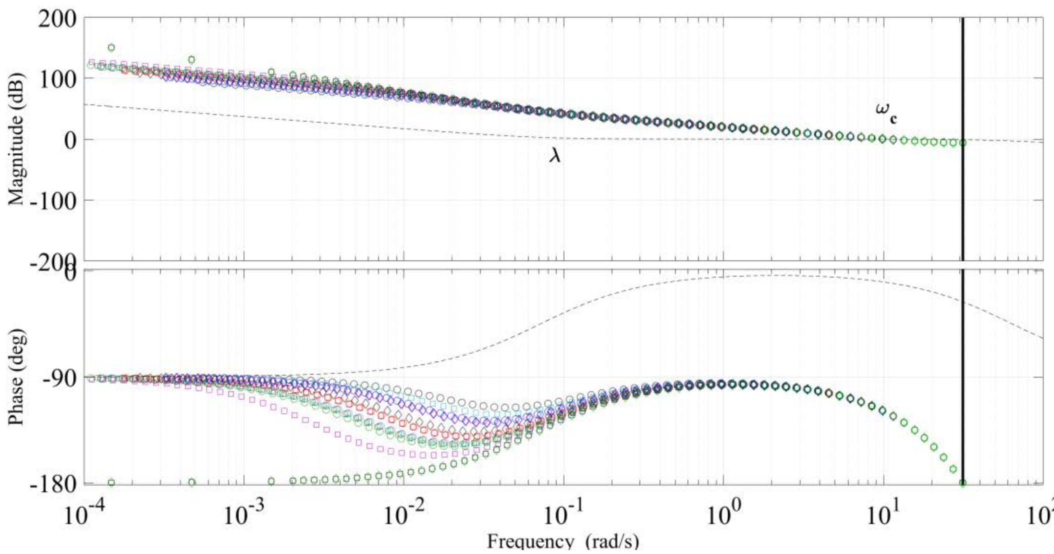

Figure 6. Frequency response for all operators.

Figure 6 shows the describing functions, $Y_p(s)$, pass the lower frequencies and attenuate the higher frequencies more. The crossover frequency is $\omega_c \geq \lambda$ and located at ~ 10 rad/sec. The phase margin can be calculated at gain crossover as $\measuredangle$ 60 degrees. The resulting frequency response is in keeping with what would be expected in a good closed-loop system. There is a tendency for the amplitude ratios to approximate -20 dB/decade slopes at the crossover frequency. Near the controllability limits the slope becomes considerably shallower than -20 dB/decade. Observed operator task delays τ were not constant; running as low as 0.5 seconds and as high as 2.6 seconds.

8.1 Intra-subject variability

The first operator variability of interest is of a run-to-run nature - an operator compared with himself when he tracks the same input successively. On examining Fig. 6 we observe that all three operators indicate run-to-run variabilities at low frequency. There is less variation in the region of crossover; this behaviour is consistent with the demands of the closed-loop system. There is evidence of constrained behaviour through the entire measurement range. The task was considered to be difficult enough to introduce brief periods of inappropriate variations in temporal action seen as time-varying phase shifts and reflected by phase variability in the measurements. It should be noted that the forcing function is not random-appearing, but is periodic over a relatively short time interval. The operator may be able to detect and anticipate the repetitive nature of the input and adjust his response accordingly. This type of behaviour may amount to the presence in the system of further signal paths and a more complex than single-loop structure.

8.2 Inter-subject variability

The impact of subjects on the variability of the describing functions may be examined in Fig.6. The same general trends as already observed for the run-to-run intra-subject changes. There is a wide in the phase for this critically difficult controlled element.

9 OUTPUT NON-LINEARITY

The linear describing function comprises one part of the quasi-linear system; the output non-linearity is an equally important component. The results of identification of the piecewise non-linearity are shown in Fig. 7. The three marker shapes represent individual operators and the different colours represent the six experiments. A positive power perturbation elicits the expected rod insertion movement from the operator; and a negative power perturbation results in a rod withdrawal. The following features are of particular interest:

I. Some evidence of pulsing behaviour in the control of the reactor is present; indicating a tendency of the operator's output to be pulses with stimulus amplitude.

II. The first negative power disturbance (leading to rod withdrawal) experiment (marked by the pink symbols) shows some evidence of inappropriate variations in operator temporal action; this is reflected in the presence of larger response overshoots and has the potential to be an indicator of increasing task complexity.

III. Overall there appears to be a reduction in maximum magnitude of the input to non-linearity with successive individual operator tests. The operators may be adjusting their characteristics to prevent large power excursions in the transient; this could potentially become an indicator of operator task-learning and requires further investigation.

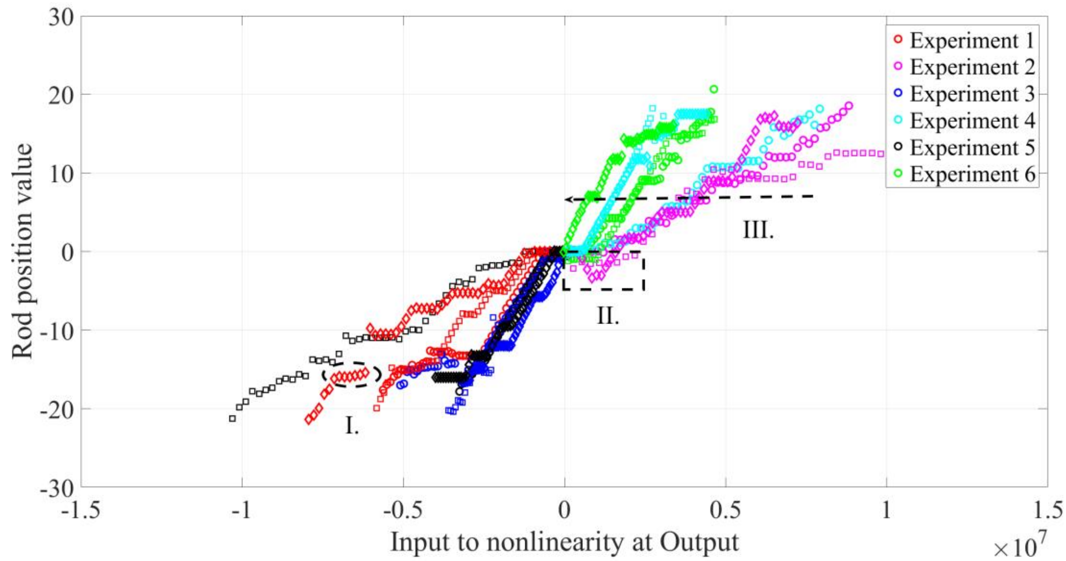

Figure 7. Intra- and inter-subject non-linearities.

Each subject may have their own style of operation and this is reflected in changes in the describing function model in those regions away from crossover where the form of the model is not critical to good disturbance control. As the reactor approaches critical the operators behave nearly identically under the constrained conditions. The shape of the open-loop function away from the gain crossover frequency is usually almost irrelevant to the closed-loop performance.

10 CONCLUSIONS

Investigations into reactor handling qualities and methods for identifying operator-reactor characteristics based on the methods of control engineering theory are evolving and are in the process of construction and refinement. This study has heightened the desire for, and increased the potential importance of, a more complete understanding of the mathematically describable aspects of human dynamics in reactor control systems.

Extensions to the current research programme may include:

1. An expanded data collection serial to encompass additional reactor types and increased operator numbers; resulting in a comprehensive database capable of increase confidence and precision in operator-reactor research.

2. Broadening of the operator task types to include visual- and audio-input tracking.

3. Development of the combined experimental-analytical approach to investigate the following effects on reactor handling:

    (a) display and manipulator interface variations, and

    (b) operator training programmes and increased workloads.

4. Analysis of the variation of operator-reactor handling characteristics with forcing function power spectrum.

5. Predictions of manual control system performance in future reactor designs. The new knowledge gained from this programme should have significant impact both on the content and nature of the information displayed to reactor operators and on the designs of manipulative devices with which the operator controls the reactor.

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Any views expressed herein are those of the author(s) and do not necessarily represent those of Defence Academy of the United Kingdom.

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