IDENTIFICATION AND SYSTEM PARAMETER ESTIMATION METHODS FOR A PYROFUSION NEUTRON SOURCE

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ABSTRACT

Pyrofusion sources are compact, low power systems which are capable of producing short intense pulses of neutrons from D-D fusion reactions. A model structure has been derived from the underlying physics principles and it is shown that the dominant non-linear dynamics pose significant challenges to the system control. This paper presents the methods under development to construct, estimate and analyse non-linear grey-box models of pyrofusion systems from measured data. The methods have been trialled on data sets obtained from the publications of previous pyrofusion research groups. The results indicate the promising potential application of these methods to the system identification of profusion device characteristics to support model verification, pulse characterisation and prediction of operational capabilities. The identified models are shown to exhibit satisfactory analogous cause-and-effect behaviour.

Key Words: pyrofusion neutron dynamics, system identification

1 INTRODUCTION

Previous pyrofusion research groups have focused efforts on the development of the hardware to increase the neutron flux, [1], [2], [3]. This paper introduces the development of system identification models and parameter estimation methods in MATLAB/Simulink to support the predictability and control of the generated neutron pulse. The pyrofusion dynamic models currently under development may be used for:

1. Estimation of pyrofusion system dynamic response, stability and performance.
2. Determination of controllable pyrofusion dynamics and controllability boundaries.
3. Indication of the type of additional system equalization desirable to achieve better control.
4. Identification of the maximum forcing function bandwidth compatible with reasonable control action.

2 PYROFUSION SYSTEM

The data selected for identification is that of the University of California Los Angeles (UCLA) [1]. The UCLA system comprises a single z-cut, 1 cm radius, LiTaO3 crystal with its -z axis facing a deuterated target in a vacuum chamber containing 0.7 Pa of deuterium gas. Figure 1 shows a typical single crystal configuration. In UCLA experiments the crystal is heated from 240 K to 265 K resulting in a decrease in spontaneous polarisation and leading to a system potential of around 100 keV.

For this particular system geometry. A tungsten tip was used in these experiments to generate a high electric field, (> 25 Vnm^{-1}) sufficient for ionisation of deuterium and acceleration of the ions into a deuterated target. A neutron flux over 400 times the background level was reported.

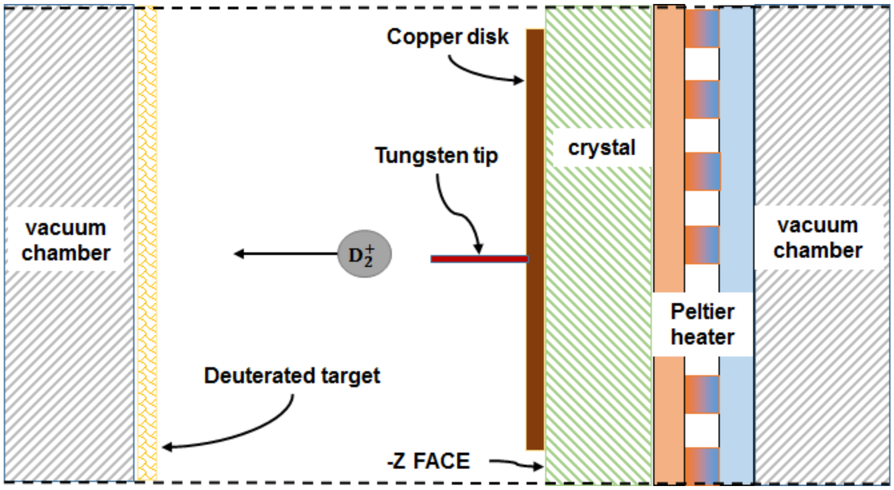

Figure 1. Schematic of the main components of a single crystal pyrofusion system.

3 MODEL ESTIMATION

Mathematical dynamic relationships between the input and output experimental data of each sub-system may be estimated with the implementation of the system identification algorithms in MATLAB. With consideration to the available system data, three potential sub-systems may be identified:

1. Temperature to system potential (x-ray energy),
2. potential to ion current, and
3. ion current to neutron flux.

The selected time-domain data captures the important sub-system dynamics, such as the dominant time constants, system natural frequency and damping. Input and output objects are extracted from the published data plots using MATLAB, and de-trended to remove specific offsets leaving perturbations around the system operating points. Continuous-time and discrete-time models were estimated from the time-domain data for both linear and non-linear differential equations. Systems were represented as grey-box models and coefficients were estimated from the experimental data. The simulated model response comparison results are shown in Figures 2, 3, and 4. Each plot shows the simulation comparison for the following model structures:

- Solid lines (black) are the original experiment data sets.
- Dashed lines (blue) are the first-order transfer function model estimates.

- Square markers (red) indicate the identified second-order transfer function model estimates.

- Circle markers (yellow) indicate the identified Hammerstein structured non-linear models with first-order describing function and an appropriate static non-linearity.

- Diamond markers (purple) indicate the identified Hammerstein structured non-linear models with second-order describing function and the non-linearity.

The three sub-systems may be individually analysed:

1. **Temperature to x-ray energy**. Two linear models of first- and second-order structure were estimated. Two non-linear Hammerstein models were also estimated; these consisted of a dead-band in series with describing functions of order based on the previously identified linear models. The estimated second-order non-linear model simulates the temperature potential experimental data relationship with a good fit of ~ 85%. The identified dead-band interval indicates a required ~ 25 K for domain switching in a LiTaO3 crystal with an initial temperature of 240 K and heating rate of ~ 12.4K min^{-1}.

2. **Potential to ion current**. The first-order transfer function estimation is shown to have the worst fit. The estimated second-order non-linear model with a dead-zone of [0, 80 keV] was the most appropriate structure for the ionisation model, having a reasonably good percentage fit of ~ 89%.

3. **Ion current to neutron flux**. Second-order linear and non-linear model structures for the input-output data of the neutron flux sub-system yielded unacceptable estimations, with poor fit. The most appropriate of the estimated models is the first-order non-linear model, having a good percentage fit of ~ 94%.

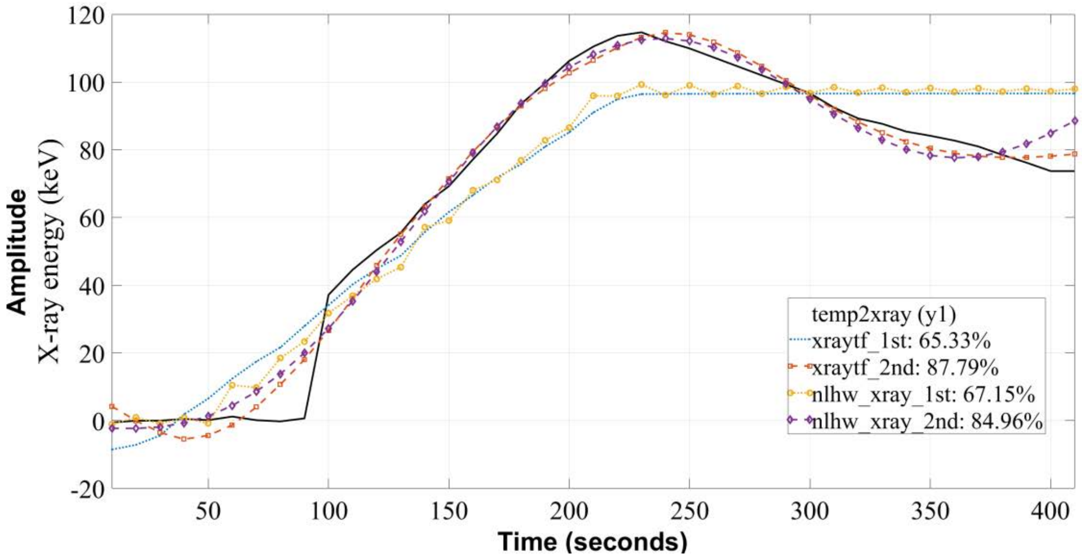

Figure 2. X-ray model estimate.

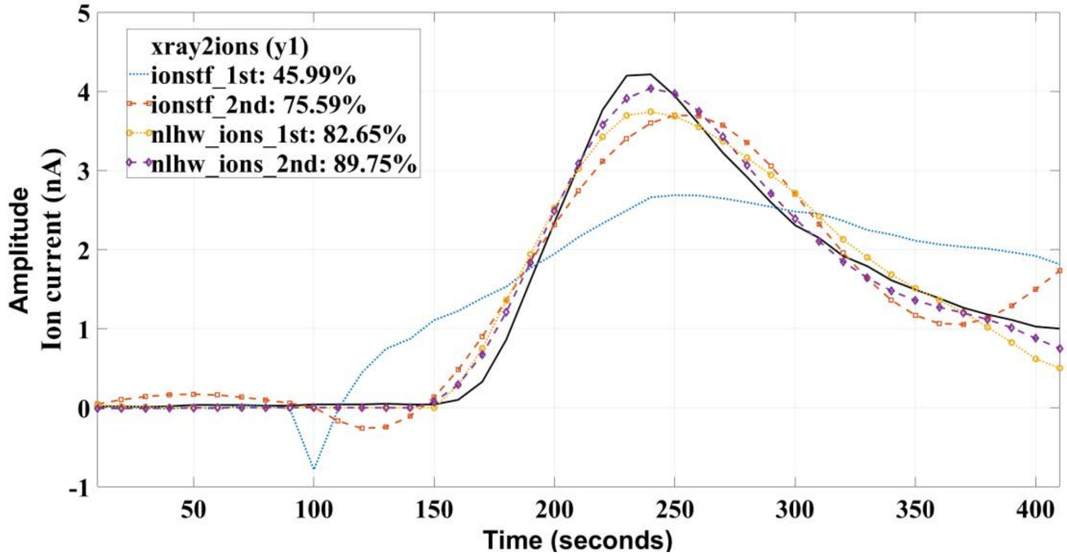

Figure 3. Ion model estimation.

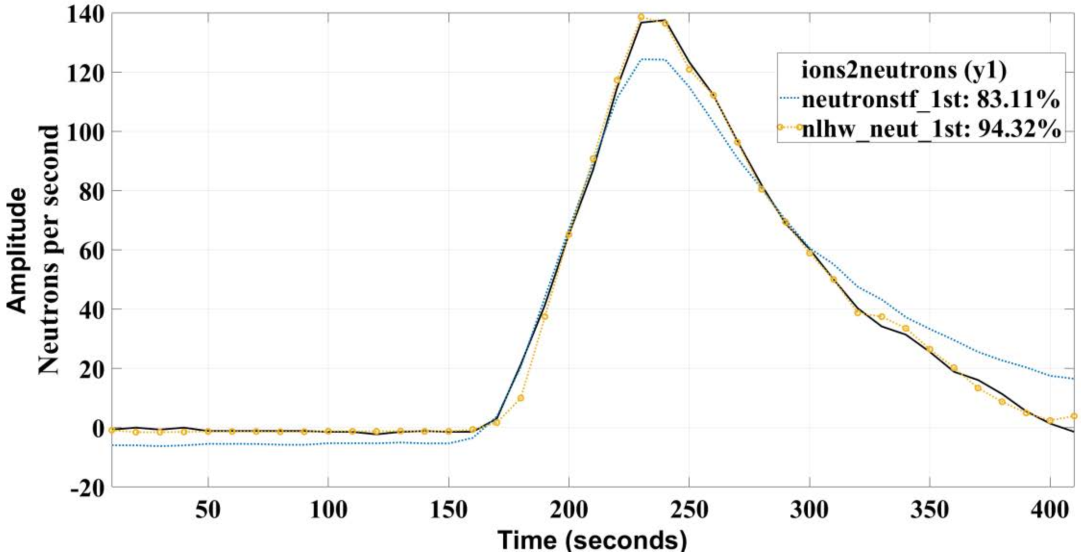

Figure 4. Neutron model estimation.

4 INTERPRETATION OF RESULTS

The identified pyrofusion model may be implemented in Simulink as shown in Fig.5. The simulated system response is shown in Fig. 6; the solid (black) lines represent the experimental data, and the dashed (blue) lines are the simulated Simulink model response.

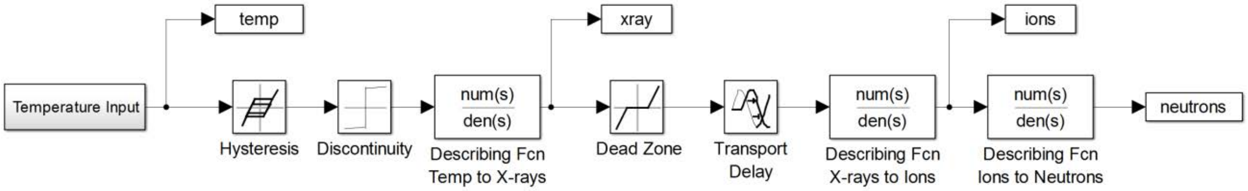

Figure 5. Schematic of estimated Simulink model with non-linearities.

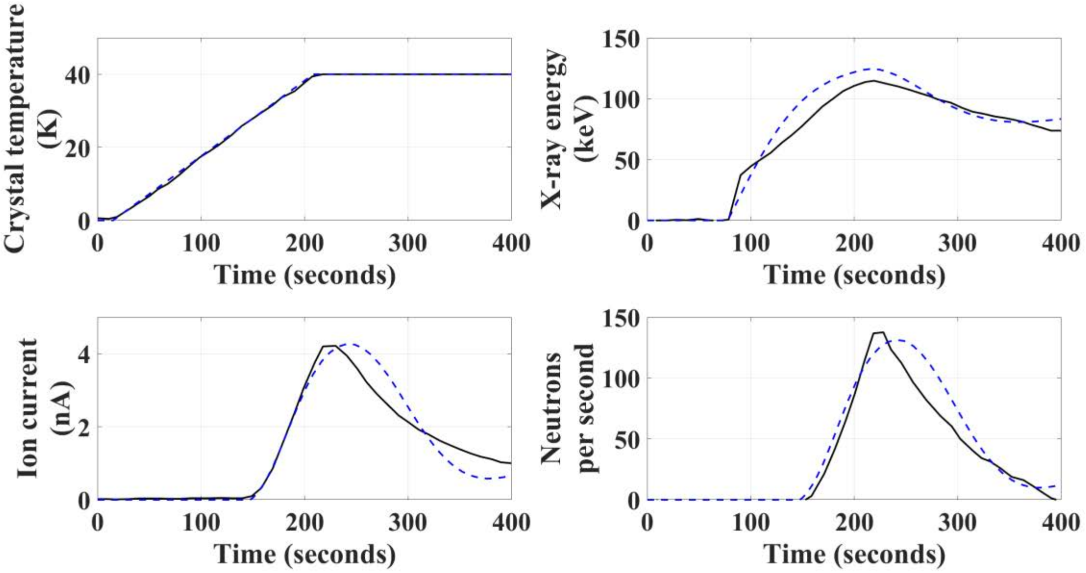

Figure 6. Comparison of data and model simulated response.

Each sub-system of the model is represented by a linear describing function and the appropriate non-linearities:

1. **Temperature to system potential (x-ray energy)**. The polarisation hysteresis loop (implemented by a combined hysteresis and discontinuity elements in series) is an unavoidable non-linearity in the heated pyroelectric crystal. The hysteresis is in part due to a time temperature dependence of

realignment of the internal crystal field after domain switching [4]. The identified temperature-potential describing function was

$$0.11375\frac{s + 0.01136}{s^2 + 0.02273s + 0.0006167}$$

2. **Potential to ion current**. A dead-zone of [0,80 keV] was identified for the ionisation model, this is in good agreement with reports of rapid field ionisation observed at t = 150 seconds during the UCLA experiments. A transport delay was identified as a required nonlinear element for improved model response - this non-linearity may potentially represent ion mobility and drift velocity across the vacuum chamber which in reality is a function of ion-gas temperature. The identified potential-ion current describing function is

$$-0.00047732\frac{s - 0.04881}{s^2 + 0.003022s + 0.001022}$$

3. **Ion current to neutron flux**. A potential neutron flux model was identified as

$$31.642\frac{s - 0.0004984}{s}$$

For the particular system operating point, initial conditions, and temperature input profile, it was found that this could reasonably be approximated as a pure gain (K~35). The frequency response of each system is shown in Fig.7, indicating that the individual subsystems are stable; however, the overall system represented may be unstable at particular operating points. In Fig.7;

- The dashed line (blue) represents the temperature - X-rays second-order describing equation,
- the dotted line (red) represents the X-rays - ion current second-order describing equation,
- the dash-dot line (yellow) represents the ion current-neutron flux first-order describing equation, and
- the solid line (purple) represents the full system describing equation.

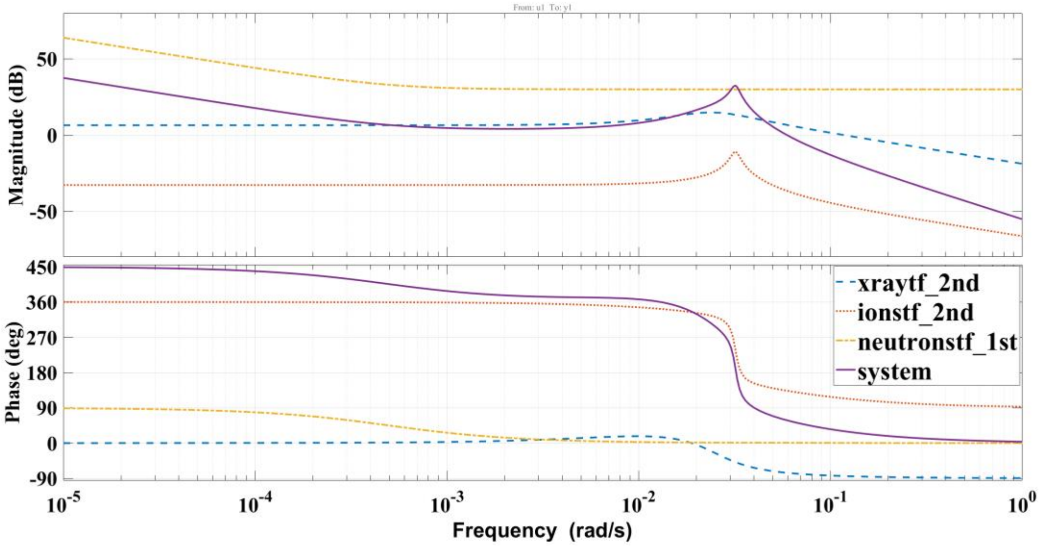

Figure 7. Frequency response for estimated models.

5 CONCLUSIONS

The models are valid in that their behavioural properties reasonably resemble the performance of the pyrofusion system. Extensions to the research programme may include:

1. Development of methods for identifying the non-linear and time-varying dynamic characteristics for a range of pyrofusion systems with various operating points.
2. Investigations into the physical identification of the model structures through pyrofusion experiments.
3. The use of measured parameters to calculate figures of merit for a variety of pyrofusion system configurations.

6 ACKNOWLEDGMENTS

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

7 REFERENCES

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