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Low-risk Beginning of the Density Feedback Control in KSTAR

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During the early campaigns of the KSTAR projgect, feedback control of plasma density has been successfully commissioned at the very first attempt by using a transfer function analysis. A stable and robust discharge was chosen as a test-bed i.e. a 300 kA (I_p) 2.0 T (B_t) ohmic circular limited plasma. Before direct feedback control, pre-programmed fueling modulation was carried out by puffing the deuterium gas. Line-averaged plasma density was measured in real-time by a 280 GHz interferometer system. From the open-loop experiments, both the density decay time (τ_i^*) and the external fueling efficiency (f_{ex}) were obtained approximately : 3.0 to 5.0 s and 10 to 20 % respectively. By transfer function analysis, several transient responses such as rising time, settling time and overshoot ratio were estimated in a certain range by the measured ranges of τ_i^* and f_{ex}. It is found that τ_i^* has little effect on those response characeristics while f_{ex} plays primary role together with magnitude of the proportional gain K_p. This is due to predominance of valve response whose characteristic time τ_v was approximately determined as 60 ms by dusing D_α signal, which is much shorter than τ_i^*. Considering these values, K_p for closed-loop control were initially set 2.5 as minimum and followed by stepwise increment to reduce steady-state error without any integral gain K_i to avoid any uncertainty. The small K_p was chosen being concerned on excessive fueling if any unexpected result happens. Similarly the target density waveform was also set low initally liniearly increasing until a flattop period for one second before current ramp-down. In this way the first density feedback control was successfully finished although the transient responses were far different from the experimental result while the predicted steady-state error was in good agreement with the experimental undershoot. By replacing τ_v with arbitrary characteristic time τ_a two different settling time in the two subsequent feedback experiments were both matched well with a single $\tau_a \sim 120ms$. This is due to a digital low-pass-filter included by a plasma control system (PCS) acting as 50 ms delay of response. Including the filter, transfer function becomes 3-pole system and no more simple analytic expression of response characteristics were avaliable. Instead, they were fully numerically computed. The changed settling times including the digital filter matched well with $\tau_a \sim 50ms$ which became much closer to the original τ_v. In summary, response characteristics in longer period (settling time and steady-state error) are evaluated well with the transfer functions in considering simple particle balance model with fixed τ_i^* and f_{ex} and fueling delay estimated by D_α signal including digital filter. However rising time and overshoot still does not agree with any values of τ_a, which implies the density feedback system is not simply the second or third order or even linear system. For more accurate prediction of response, therefore, nonlinear or time-varying numerical model will be necessary especially in dealing with the recycling coefficient R that underlies in $\tau_i^* \equiv \tau_i/(1-R)$ where τ_i is particle confinement time.

Author: Dr JUHN, June-Woo (National Fusion Research Institute)

Co-authors: HAHN, Sang-hee (National Fusion Research Institute); HWANG, Yong-Seok (Seoul National University); Mr KIM, K. P. (National Fusion Research Institute); Mr KIM, Y. O. Kim (National Fusion Research Institute); Dr NAM, Y. U. (National Fusion Research Insitute); Mr SONG, J. I. (National Fusion Research Institute)

Presenter: Dr JUHN, June-Woo (National Fusion Research Institute)

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