

## Low-risk Beginning of the Density Feedback Control in KSTAR

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During the early campaigns of the KSTAR project, 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 ( $\tau_i^*$ ) 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  $\tau_i^*$  and  $f_{ex}$ . It is found that  $\tau_i^*$  has little effect on those response characteristics 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  $\tau_v$  was approximately determined as 60 ms by using  $D_\alpha$  signal, which is much shorter than  $\tau_i^*$ . 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 initially linearly 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  $\tau_v$  with arbitrary characteristic time  $\tau_a$  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 available. 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  $\tau_v$ . 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  $\tau_i^*$  and  $f_{ex}$  and fueling delay estimated by  $D_\alpha$  signal including digital filter. However rising time and overshoot still does not agree with any values of  $\tau_a$ , 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  $\tau_i$  is particle confinement time.

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