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Spatial Structure of Compound Dither in L/H Transition

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To study the plasma evolution and spatial structure at the L/H transition, the double hysteresis is examined by use of the 1-dimensional transport model equations. Three mechanisms for the bipolar losses, i.e., the loss cone loss, collisional bulk viscosity loss of ions and the anomalous loss are simultaneously retained. Five-fold multiple bifurcations are found to exist at the plasma edge, similar to the previous 0-dimensional study. Double hysteresis causes a self-generated oscillation, which is attributed to the compound dither, a kind of ELMs. Spatio-temporal evolution of the compound dither is analyzed.

KEYWORDS H-mode, double hysteresis, transport barrier, ELMs, dithers

§1. Introduction

Transition phenomena in plasmas (e.g., L/H Transition) are widely observed in various toroidal devices and mirror devices. The hysteresis characteristic has been observed in the L/H transition[1] and in the various collapse events.[2] The model based on the electric field bifurcation has been proposed to understand the H-mode.[3] In this study, multi-fold relation between the gradient and flux is predicted, i.e., the hysteresis characteristic was derived, considering the loss cone loss of ions and the anomalous loss. The transport barrier is predicted by this model, when the spatial structure was examined by use of the 1-dimensional (1-d) model equation. The model equation is also applied[4] to study the dynamics of the transport barrier. At the edge, the self-generated periodic oscillation of the particle flux is theoretically obtained, which is attributed to the experimentally-observed dithering ELMs.[5] Dithering ELMs are observed in the vicinity of the threshold of the L/H transition. The other kinds of ELMs, (Type I, Type III), have been observed away from the threshold of L/H transition, and are considered as MHD phenomena in experiments (see e.g., a review[5]). The theoretical analyses were reported for Type I and III ELMs in the framework of MHD instabilities and large scale turbulence.[1,6-10] Variation of Type I ELMs has been reported, in DIII-D, namely, ELMs of relatively long duration up to $\approx 10ms$ were found. It was pointed that these long events, 'compound ELM', can be described as an initial MHD instability followed by a transient L-mode.[11] Recent review of the theory of ELMs is given in ref. 12. Variety of ELMs could be more abundant than Type I, Type III and dithers.

Model theory for L/H transition is required to have 'hard' transition (i.e., hysteresis characteristic) to show the fast time scale as the transition. (See e.g., ref. 13 for a review.) It is now widely accepted that the radial electric field plays an important role in the H-mode transition. Several possible mechanisms have been reported, including an ion loss cone loss,[3,14] ion bulk viscosity loss,[14] anomalous loss,[3,15] Stringer spin-up due to poloidal asymmetries in turbulent transport[16] and the external biasing.[17] The hard type bifurcation is predicted from the stationary condition. Other model of the L/H transition were presented driven by the soft type transition[18] of the electric field shear.[15,19,20] (In this case, the variation from the low confinement state to the high confinement state can occur by following a smooth change.) The inclusion of the effect of the electric field shear on the ion loss cone loss and the anomalous loss gave the variety of the bifurcation.[21] For the mode of the hard type bifurcation, the hysteresis in the gradient-flux relation could be more complicated than the one in ref. 3, when these mechanisms are simultaneously analyzed. For example, the 0-dimensional (0-d) analysis[22] have compared the impacts from the loss cone loss, collisional bulk viscosity loss of ions and the anomalous loss. This study has shown that there exists a parameter regime where the five-fold solutions at the fixed gradient appear. In this parameter region, two different hysteresis are found to co-exist. This characteristic is called 'double hysteresis'. Due to double hysteresis, the new kind of periodic oscillation was obtained, and 'compound dithers' in experiments were predicted. (Note that this kind of ELMs, 'compound dithers', is different from 'compound ELMs'; the dithering cycles do not show the MHD features but the sequence of the L/H transitions, and compound dithers are predicted to occur near the L/H transition threshold.) If 'compound dithers' are obtained in experiments near the threshold power of L/H transition, the competition of the bipolar losses will be found to contribute the mechanisms for the L/H transition. Here, we focus on the analysis of 'compound dithers' in this article. This result was obtained by use of the 0-d model. It is necessary to investigate

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what kind of dynamics and spatial structure is generated from these three important mechanisms (an ion loss cone loss, a collisional bulk viscosity loss, and an anomalous loss) in 1-d transport equations. This would give a key to understanding the complex features of ELMs in experiments, for which understanding and control are urgent tasks.

In this article, we shall show the spatial-temporal structure at the L/H transition, in which the double hysteresis characteristic is included. We use the one-dimensional transport which involves the temporal evolutions of the density and the radial electric field. Three kinds of the bipolar flux mechanism, the loss cone flux of ions, the ion bulk viscosity flux and anomalous flux are examined similar to the study in ref. 22. Compound dither is found to be self-generated. Spatial and temporal structure of the compound dither is presented. It is also shown that the 0-d model can provide a qualitatively relevant solution for compound dither in comparison with 1-d analysis.

§2. Model Equation

2.1 One-dimensional model equations

The plasma of our interest is restricted to the plasma boundary $-L < r - a < 0$, where a is the minor radius. Plasma parameter is assumed to be constant in the toroidal and poloidal directions, in this article. Thickness of layer is much thinner than the plasma radius and the plasma boundary is modelled by the slab plasma in this article. Cartesian coordinates are used, and the x-axis is taken in the radial direction, where $x = r - a$. The relation between the coordinates r and x is shown in Fig. 1. Plasma profiles are described by keeping the x-dependence, and the one-dimensional transport equation is employed.

Minimal model of the dithering ELMs contains dynamics of two physical quantities: one plasma parameter and the radial electric field.[4] We follow the consideration of ref. 4, and adopt two basic equations: One is the temporal evolution of the density. The other equation is the temporal evolution of the radial electric field derived from the momentum equation in the poloidal direction. We fix the temperature temporally and spatially. Dithering cycles are derived from even only the flux-gradient relation of the density. The analysis in ref. 23, in which the temperature evolution is also included in addition to the density evolution, shows that additional temperature dynamics does not change the essence. Based on these analyses, we choose the analytic simplifications, i.e., constant temperature profile of T_e and T_i. (These relations, $T_e' = 0$ and $T_i' = 0$, hold, where the prime denotes the derivative with respect to the radial direction.) Here, T_e and T_i are the temperature of electrons and ions, respectively. We use the quasineutrality, $n_e = n_i (\equiv n)$, where n_e and n_i are the density of electrons and ions, respectively. The set of equations is given dimensionless form, which shows the ions' equation of motion, as

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}(D(Z)\frac{\partial n}{\partial x}) \tag{2.1}$$

and

$$\epsilon\frac{\partial Z}{\partial t} = \hat{\Gamma}_e - \hat{\Gamma}_i + \mu\frac{\partial^2 Z}{\partial x^2}, \tag{2.2}$$

where n is the density, $Z = e\rho_{pi}E_r/T_i$, e is the unity of charge, E_r is the radial electric field, ρ_{pi} is the poloidal gyroradius and μ is the normalized value of the shear viscosity μ_i of ions. Here, $\hat{\Gamma}_e - \hat{\Gamma}_i$ represents the bipolar component of the particle flux, where $\hat{\Gamma}_e$ and $\hat{\Gamma}_i$ are the normalized particle flux of electrons and ions, respectively. The form of the particle flux will be shown in the next subsection. The point which holds the relation $x = 0$ represents the plasma edge and ϵ indicates the smallness parameter $O(B_p^2/B^2)$, where B_p and B are the poloidal and toroidal magnetic field, respectively. Here, the diffusivity D of ions in eq. (2.1) is modelled as

$$D(Z) = (D_{\max} + D_{\min})/2 + ((D_{\max} - D_{\min})/2)\tanh Z. \tag{2.3}$$

Here, D_{max} corresponds to L-mode conditions and D_{min} to the H-mode. To obtain the smoothness of the function, we choose the hyperbolic tangent as the function of the electric field Z for the diffusivity. The normalizations are followed as $x/\rho_{pi} \to x$, $D/D_{c0}^b \to D$, $\mu_i/D_{c0}^b \to \mu$, $tD_{c0}^b/\rho_{pi}^2 \to t$, where D_{e0}^b is the bipolar part of the electron effective diffusivity. The subscript '0' represents the typical value for L mode. The parameters μ, D_{max} and D_{min} are chosen to be constants. The term $\hat{\Gamma}_e - \hat{\Gamma}_i$ derives the nonlinear relation between the particle flux and the density gradient. The third term in the right hand side of eq. (2.2) shows the diffusion effect of the radial electric field Z. The influence of the inhomogeneous electric field on the anomalous transport is governed by the parameter $H_1 \equiv (T_i/(e\gamma_{dec}B\ell\rho_{pi}))^2$, where γ_{dec} is the decorrelation rate of turbulence which causes anomalous transport. Here $\ell = \sqrt{\mu_i/\sigma(0)}$, where $\sigma(0)$ is the conductivity in the absence of the radial electric field.[13] When the condition $H_1 Z_*^2 < 1$ is satisfied, the assumption of the constant viscosity was shown to be valid.[24] In this expression, Z_* is the normalized radial electric field at which the bipolar flux $\hat{\Gamma}_e - \hat{\Gamma}_i$ takes the extremum. The assumption that μ, D_{max} and D_{min} are independent of the gradient of the electric field means that the cases of $H_1 Z_*^2 < 1$ are analyzed here.

2.2 Models of bipolar losses

We choose three mechanisms that causes the bipolar particle flux, i.e., the loss cone loss, collisional bulk viscosity loss of ions and the anomalous loss. For the loss cone loss of ions, we employ the generalized form in ref. 25

$$\Gamma_i^{lc} = \frac{n_i\nu_i\sqrt{\epsilon}\rho_{pi}}{(\nu_{*i} + Z^4)^{1/2}}\exp\left(-(\nu_{*i} + Z^4)^{1/2}\right), \tag{2.4}$$

where ν_{*i} is the the effective collisionality of ions, which is defined as $\nu_{*i} = \nu_i/\omega_b$. Here, ν_i is the ion-ion collisional frequency and ω_b is the bounce frequency of ions. Assuming $E_r = -U_p/B$ (U_p is the poloidal velocity of plasmas), the model for the bulk viscosity loss of ions[25] due to the magnetic field is rewritten as (if $T_i' = 0$.)

$$\Gamma_i^{bi} = \frac{n_i \epsilon^2 \sqrt{\pi} \rho_{pi} I_p}{4r} \left(Z - \frac{\lambda}{2} \right), \tag{2.5}$$

where ϵ is the inverse aspect ratio, λ is the thermodynamic force defined as $\lambda = -\rho_{pi} n'/n$ and the detail about integral I_p is given in ref. 25 as

$$I_p = \frac{1}{\pi} \int_0^{\sqrt{\nu_{*i}}} dx\, x^2 exp(-x^2) \int_{-1}^{1} d\left(\frac{v_\parallel}{v}\right) \left[1 - 3\left(\frac{v_\parallel}{v}\right)^2\right]^2$$
$$\times \frac{\nu_{*i} \epsilon^{\frac{3}{2}} (\nu_T/(\nu_i \sqrt{x}))}{(v_\parallel/v + (Z + \lambda/2)/\sqrt{x})^2 + \left[\nu_{*i} \epsilon^{\frac{3}{2}} (\nu_T/(\nu_i \sqrt{x}))\right]^2}, \tag{2.6}$$

where v is the particle velocity, $x = v/v_T$, and ν_T is the the collision frequency for the anisotropy relaxation.[26] The model for the anomalous bipolar loss has been discussed in ref. 3 and then by others in terms of the Reynolds' stress of turbulence.[13] We here employ a simplified expression for the anomalous bipolar loss as (if $T_c' = 0$,)

$$\Gamma_{c-i}^{anom} = -D_c^b \left(\frac{n_c'}{n_c} + \frac{eE_r}{T_c}\right). \tag{2.7}$$

In the dimensionless form, we have

$$\widehat{\Gamma}_c - \widehat{\Gamma}_i = \widehat{\Gamma}_{c-i}^{anom} - \widehat{\Gamma}_i^{lc} - \widehat{\Gamma}_i^{bv}, \tag{2.8}$$

where

$$\widehat{\Gamma}_{c-i}^{anom} = d(\lambda - Z), \tag{2.9}$$

$$\widehat{\Gamma}_i^{lc} = \frac{\nu_{*i}}{(\nu_{*i} + Z^4)^{1/2}} \exp\left(-(\nu_{*i} + Z^4)^{1/2}\right), \tag{2.10}$$

and

$$\widehat{\Gamma}_i^{bv} = \frac{\sqrt{\pi} I_p}{4} \left(Z - \frac{\lambda}{2}\right). \tag{2.11}$$

Here, $d = D_c^b/(\sqrt{\epsilon} \rho_{pi}^2 \omega_b)$.

2.3 boundary condition

Boundary conditions are given at the surfaces $x = 0$ and $x = -10$. Here, we assume $L = 10\rho_{pi}$. At the plasma surface, we impose the boundary condition

$$n'/n = const.\ (x = 0). \tag{2.12}$$

From the core side, plasma flux is assumed to be constant. The plasma is in the L-state at $x = -10$ and particle flux from the core region (at $x = -10$) is treated as a parameter with

$$\Gamma = \Gamma_{in}\ (x = -10). \tag{2.13}$$

§3. Structure and dynamics of compound dithers

We solve eqs. (2.1) and (2.2) with the boundary conditions (2.12) and (2.13). We find a solution with a limit cycle including the double hysteresis characteristic of the edge density $n(x = 0)$ and the particle flux at the edge Γ_{out}.

The parameters we choose are as follows, from the condition for the double hysteresis of 0-D analysis. We take

$$D_{max} = 0.1, D_{min} = 0.005\ and\ \mu = 1 \tag{3.1}$$

to characterize the transport coefficients. The boundary conditions are chosen as

$$r_n = 1.25\ and\ \Gamma_{in} = 3, \tag{3.2}$$

where $r_n = -n/n'(x = 0)$. Furthermore, we choose $\epsilon = 0.01$ and $d = 0.1$. These parameters are constant in time in solving eqs. (2.1) and (2.2).

The initial value of the plasma parameter is specified by the value

$$\nu_{*i} = 2 \tag{3.3}$$

This value changes according to the evolution of n.

A periodic oscillation is obtained in a limited regime of the parameter near the transition layer between L and H modes. In Fig. 2, we show the typical temporal trace of edge density $n(x = 0)$. The temporal evolution of Γ_{out} is shown in Fig. 3. Furthermore, we obtain the Lissajous figure on the Γ_{out}-$n(x = 0)$ plane in Fig. 4. The L mode corresponds to the branch of the large flux and H mode is the branch of the reduced flux. The hysteresis ($F \to A \to B \to E \to F$) appears, as has been found in ref. 3 which has neglected the bulk viscosity of ions in eq. (2.2). If anomalous loss becomes small, then the contribution of the bulk viscosity loss of ions increases, so that the new hysteresis ($C \to D$) is generated combined with the other hysteresis. In this way, the double hysteresis appears. As for the fundamental cusp, this bifurcation has the nature of cusp-type catastrophe; it disappears if d is enhanced and the bulk viscosity loss of ions becomes less important. The compound dither is again predicted theoretically in the case of the 1-D transport model equations In Fig. 5, temporal variation of the radial dependence of the diffusivity D is shown. The steep gradient of the diffusivity D is shown, which corresponds to H mode. The profile of the diffusivity D shows that the H mode is only recognized near the edge. In this case, a transport barrier with finite length can be seen in the radial profile of D. The transition from C to D obtained here occurs due to the bulk viscosity loss of ions. The radial width in which the change of D can be seen do not change in the temporal evolution in $C \to D \to E \to F \to A$. Even if the bulk viscosity flux of ions is neglected, the radial extent of the transport barrier is same as the case including the bulk viscosity flux of ions.

Furthermore, we study the dependence of the frequency f for the self-generated oscillation on the influx Γ_{in} from the core region. This dependence is shown in Fig. 6. Oscillation solution appears in a limited range of the parameters, $\Gamma_1 < \Gamma_{in} < \Gamma_2$, where Γ_1=0.63 and Γ_2=4.65. Below the limit Γ_1, the state converges to low flux mode, i.e., stationary H-phase. On the contrary, beyond the critical value Γ_2, the solution merges to the high flux state, (L-phase). The critical values Γ_1 and Γ_2 are qualitatively similar to those on 0-D analysis.

Finally, we examine the parameter range for λ and ν_{*i} in which double hysteresis occurs. This study is made by changing the effective diffusivity d. The values for λ and ν_{*i} are evaluated at the plasma edge for the H mode (state A). The condition for double hysteresis is shown by the shaded region in Fig. 7. If the effective diffusivity d takes smaller value, the value of λ becomes larger for which the double hysteresis appears. The parameter region on the λ-ν_{*i} plane for the double hysteresis in this study dose not alter very much compared to the previous 0-D analysis, if the parameters λ and ν_{*i} are evaluated by those at the plasma edge.

§4. Summary and Discussion

In this article, the radial structure of the diffusivity is examined in L/H transition in which the double hysteresis appears. The bulk viscosity loss of ions is newly included in 1-dimensional transport model equations. Therefore, the dynamics and spatial structure are studied by keeping three independent mechanisms, i.e., the loss cone loss, ion loss by collisional bulk viscosity and anomalous bipolar loss. At the edge, it is confirmed that there can be multiple bifurcations due to the double hysteresis. The coupled temporal evolution of the edge density and the particle flux is analyzed at the edge. The limit cycle with double hysteresis is obtained. This also predicts the existence of compound dither in experiments similar to the prediction in ref. 22. The condition for the double hysteresis is obtained as $d \sim 0.05$ and $\nu_{*i} \sim 1$, where d is the effective diffusivity and ν_{*i} is the effective collisionality of ions. For the range of parameters of this article, it is found that the spatial-temporal evolution does not give the large change of the condition for the double hysteresis.

In this article, the radial extent is common for the simple dithers and double dither. This result depends on the model of the ion viscosity, i.e., μ is constant. This constant-μ model applies for the case of $H_1 Z_*^2 < 1$. In the system of the model equations used here, the radial extent of the transport barrier is considered to be determined by the ion shear viscosity, and the dependence $\Delta \propto \sqrt{\mu}$ was predicted, where Δ is the thickness of the transport barrier.[4] The analytic estimation from eq. (2.2) satisfies this dependence. The possible dependence of the ion shear viscosity on the gradient of the electric field, which is important in the case of $H_1 Z_*^2 > 1$, might cause the quantitative difference of the radial structure of double dithers. There arises an interesting question whether chaotic dynamics (period doubling, intermittency and so on) would appear in the compound dither. These problems are left for future work.

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Figure captions

Fig. 1 Relation between the coordinates r and x

Fig. 2 Temporal evolution of the edge density $n(x=0)$. The parameters are $\mu = 1$, $\Gamma_{in} = 3$, $r_n = 1.25$. $D_{max} = 0.1$ and $D_{min} = 0.005$.

Fig 3 Time trace for the outflux Γ_{out}. The parameters are same as the case of Fig. 2.

Fig. 4 The Lissajous trajectory on Γ_{out}-$n(x = 0)$ plane
Fig. 5 The spatial profile of the diffusivity D.
Fig. 6 The dependence of the frequency for the obtained oscillation at the edge on the influx Γ_{in}.
Fig. 7 The double hysteresis region on the $\lambda - \nu_{*i}$ plane (shaded region).

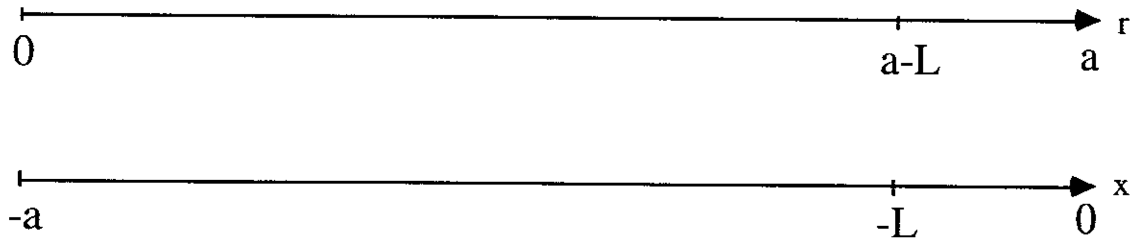


Fig. 1

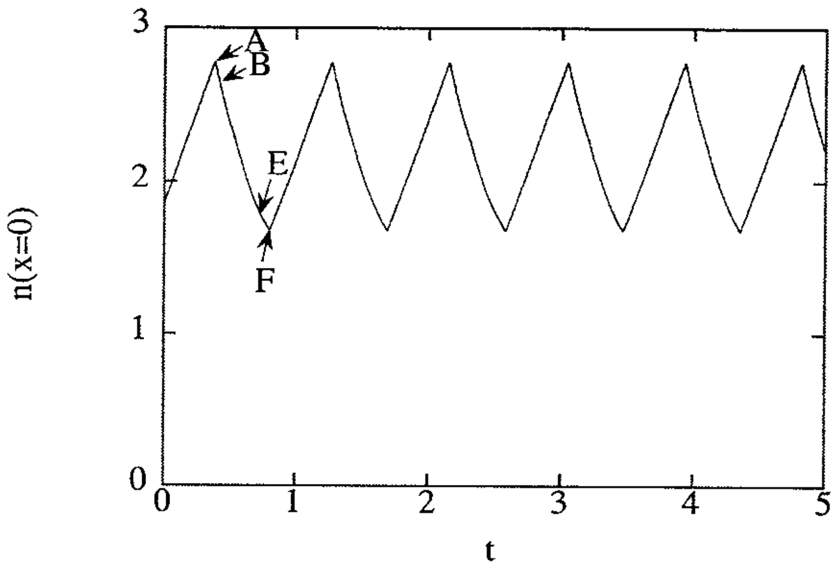


Fig. 2

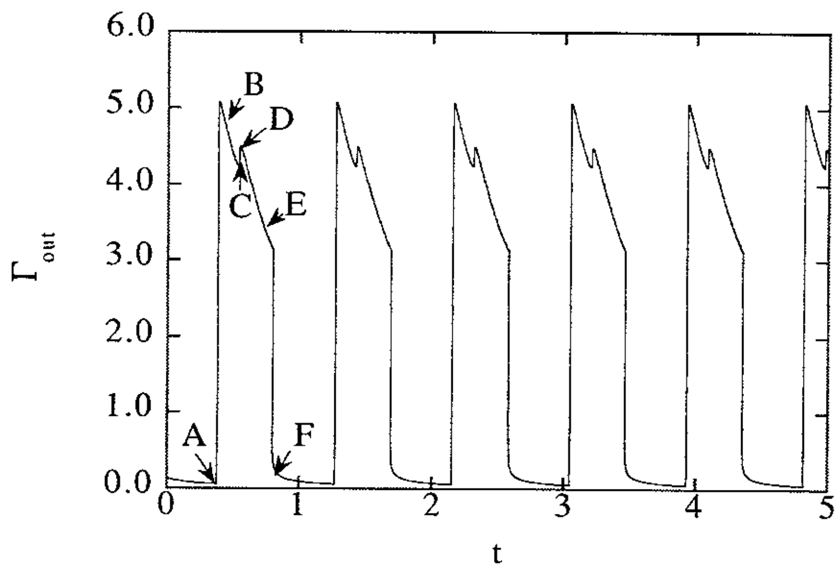
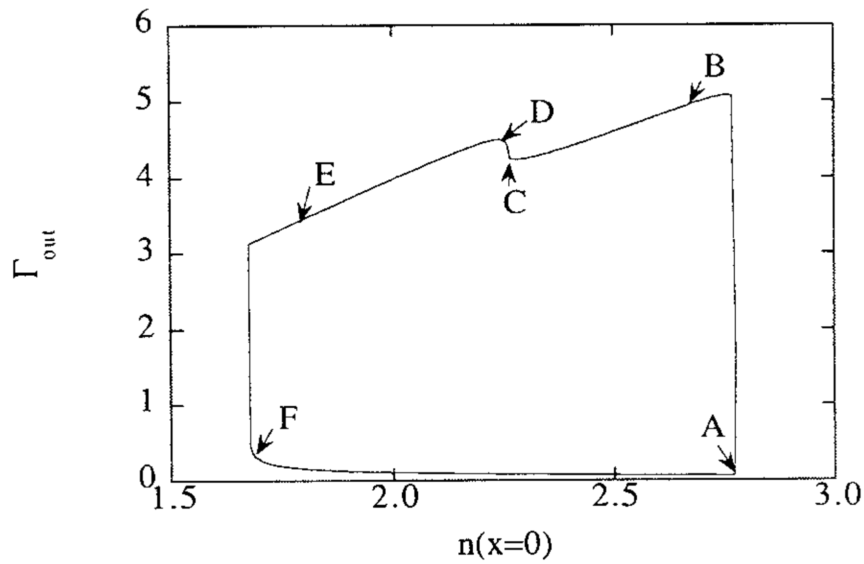
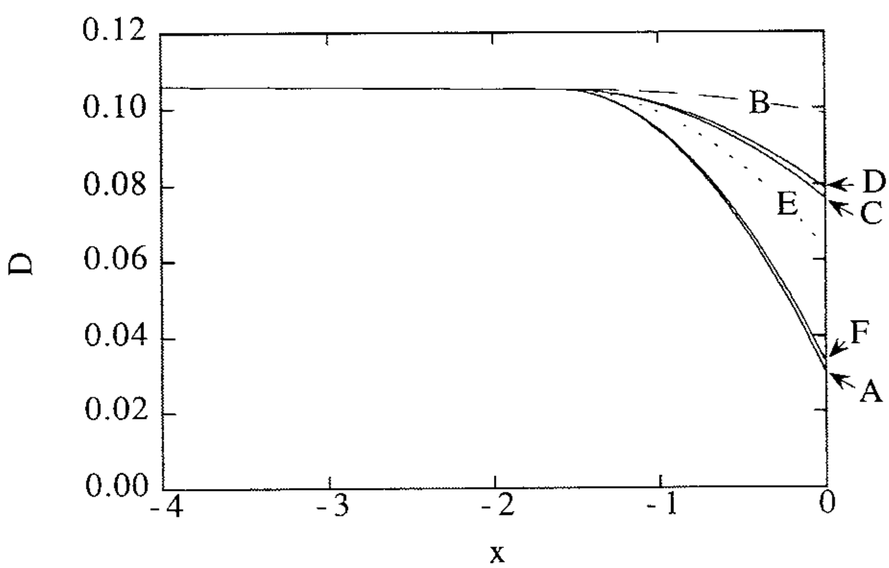


Fig. 3



6
5
4
3
2
1
0
1.5
2.0
2.5
3.0
Γ_{out}
n(x=0)
A
B
C
D
E
F

Fig. 4



0.12
0.10
0.08
0.06
0.04
0.02
0.00
-4
-3
-2
-1
0
D
x
A
B
C
D
E
F

Fig. 5

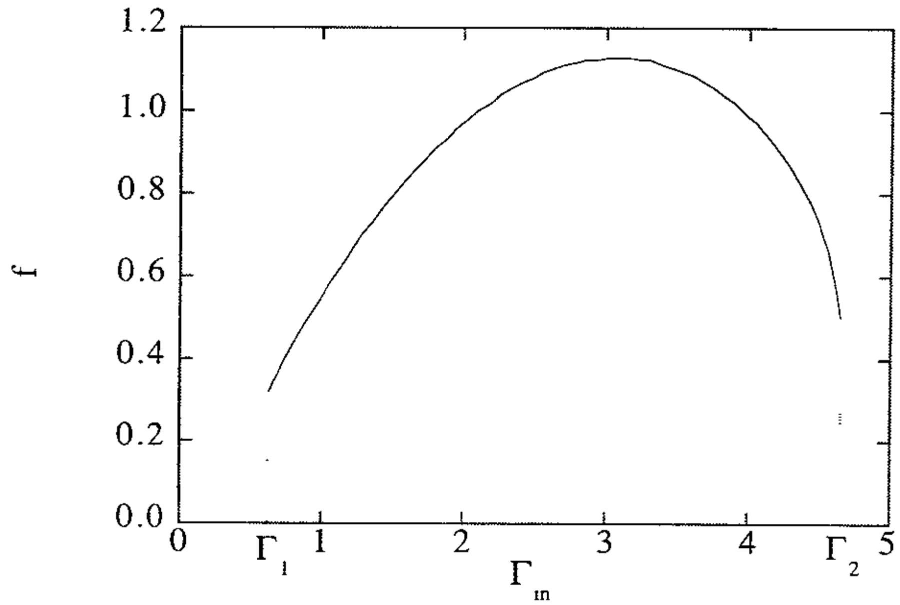

f
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
Γ_1
Γ_2
Γ_{in}

Fig. 6

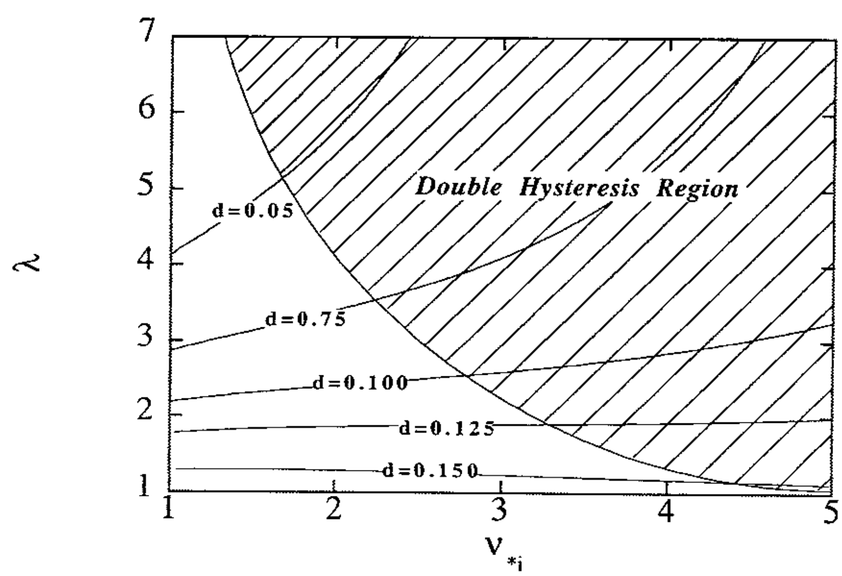

λ
7
6
5
4
3
2
1
Double Hysteresis Region
d=0.05
d=0.75
d=0.100
d=0.125
d=0.150
1
2
3
4
5
ν_{*i}

Fig. 7

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