Frequency Hysteresis of MHD Instabilities in Helical and Tokamak Plasmas

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This study examines the relationship between the amplitude and frequency of magnetic fluctuations caused by MHD instabilities in magnetically confined plasma. It reveals, for the first time, the presence of hysteresis in the amplitude-frequency relationship during both decelerating and accelerating frequency phases in helical and tokamak plasmas. This hysteresis in both phases can be explained by a torque balance model, which compares the electromagnetic braking force and the viscous accelerating force. A comparison between the two devices shows that the frequency hysteresis is primarily driven by differences in the sources of the braking force and the frequency range, rather than by the type of device. This finding can contribute to the development of a comprehensive model for the relationship between amplitude and frequency.

In magnetically confined fusion reactors, a significant issue is the rapid growth of magnetic fluctuation due to MHD instabilities after a decrease in the fluctuation frequency. This is because the growing fluctuation can lead to severe pressure gradient degradation and disruptions. If a model for the amplitude-frequency relationship independent of the device type can be established, one can predict precisely the fluctuation amplitude at the mode locking from the extrapolated value of the trajectory of the amplitude and frequency in relatively stable plasmas without disruptions in fusion reactors.

According to the torque balance model proposed by Fitzpatrick[1], the relationship between the amplitude and frequency of the magnetic fluctuation is determined by the balance between the driving forces of plasma rotation and the braking electromagnetic forces. In helical and tokamak devices such as the Large Helical Device (LHD) and JT-60U, unique amplitude-frequency trajectories of the magnetic fluctuation due to specific MHD instabilities are observed so far, and they match well with the predictions of the torque balance model [2, 3]. Here, this model considers the driving force spurred by the viscous effect and the braking force caused by the external magnetic perturbation arising from the eddy current induced by the instability or due to device-specific error fields. For the first time, the hysteresis of the amplitude-frequency trajectory is found in both LHD and JT-60U. This paper presents an extended torque balance model that explains both types of hysteresis observed in different devices.

$$F_{\mathrm{VC}} \equiv \mu(\omega_0 - \omega) \quad (1)$$

$$F_{\mathrm{RMP,slip}} \equiv \delta b \delta b_{\mathrm{RMP}} \frac{\omega\tau_{\mathrm{v}}}{\sqrt{1+\omega^2\tau_{\mathrm{v}}^2}} \quad (2)$$

$$F_{\mathrm{RMP,no-slip}} \equiv \delta b \delta b_{\mathrm{RMP}} \frac{\omega\tau_{\mathrm{v}}}{1+\omega^2\tau_{\mathrm{v}}^2} \quad (3)$$

$$F_{\mathrm{rw}} \equiv \delta b^2 \frac{\omega\tau_{\mathrm{v}}}{1+\omega^2\tau_{\mathrm{v}}^2} \quad (4)$$

List 1. Equations related to torque balance model.

Figure 1 shows the amplitude and frequency of the magnetic fluctuation in discharges where the Edge MHD instability [4] is observed in the LHD. Figure 1(a) corresponds to the case of frequency decrease, while Figure 1(b) corresponds to the case of frequency increase. Figure 1(c) shows the trajectory of the amplitude and frequency. During the frequency decrease, the frequency gradually drops as the amplitude increases (red circles). In contrast, during the frequency increase, the amplitude decreases while the frequency remains almost constant, and then the frequency increases rapidly (blue circles). The behavior during the frequency decrease aligns well with the torque balance model with a reasonable wall time constant, $F_{\mathrm{RMP,slip}}$ model (green line) that considers the driving force due to the viscous effect (F_{vc}, Eq. 1) and the electromagnetic braking force due to the external magnetic perturbation ($F_{\mathrm{RMP,slip}}$, Eq. 2). Here, δb represents the amplitude of the magnetic fluctuation, δb_{RMP} represents the amplitude of the RMP driven by external coils, ω is the different rotation frequency

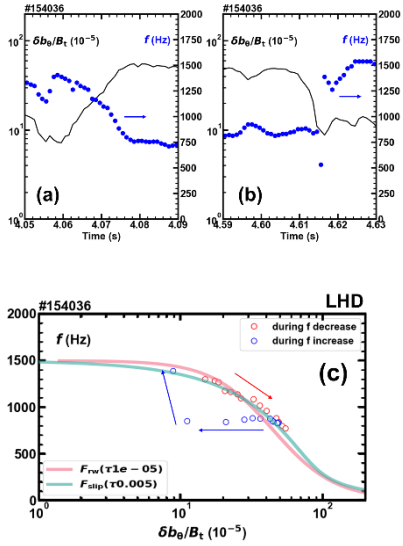

Figure 1. (a) (b) Time evolution and (c) relationship of amplitude and frequency of the magnetic fluctuation in the LHD.

between the external magnetic perturbation and plasma flow, τ_v is the wall time constant, μ is a proportional constant for the F_{vc}, and ω_0 is the rotation frequency due to viscosity or NBIs.

Figure 2 is a conceptual diagram showing the influence of electromagnetic forces in the torque balance model on frequency behavior. The green line represents the electromagnetic force, while the black line represents the driving force. Note that the crossing point means the frequency. In Figure 2(a), the frequency gradually decreases as the electromagnetic force increases with the amplitude, explaining the qualitative behavior observed during the deceleration phase in Fig. 1. However, this model does not express the abrupt frequency jump observed during the acceleration phase. In this study, a different braking force is considered. Theoretical research [1] predicts that the braking force caused by external magnetic perturbations depends on the relative velocity between the external magnetic perturbations and the frequency of the instability because of the shielding effect of the perturbation. Equation (2) represents the model for a large relative velocity, as shown in Figure 2(a), while Equation (3) corresponds to the model for a small relative velocity, as shown in Figure 2(b). In the case of Fig.2(b), the crossing point jumps abruptly when the electromagnetic force exceeds a certain threshold. Notably, the smaller relative velocity during the frequency increase phase compared to the frequency decrease phase suggests that applying the $F_{RMP,no\text{-}slip}$ model for the braking force is appropriate. The hysteresis observed in the LHD can be explained by differences in the shielding effect of the external magnetic perturbation, despite the braking force driven by the same source, that is, the external magnetic perturbation.

The hysteresis observed in JT-60U is also examined by considering the applicable model. Figure 3 shows the amplitude and frequency trajectory of the magnetic fluctuation due to the neoclassical tearing mode after the resistive wall mode observed in the JT-60U. It is important to note that, during acceleration, the frequency changes gradually, while during deceleration, frequency jumps are observed, which is different from the behavior seen in the LHD. In the previous work [3] on the frequency of the neoclassical tearing mode, where no hysteresis is observed, it is understood that the external magnetic perturbation due to eddy currents driven by the instability is the main factor behind the electromagnetic force F_{rw} (Eq. (4)) during both deceleration and acceleration. It should be noted that the F_{rw} model expresses a gradual frequency change in the high frequency band, but the abrupt frequency jump occurs in the low frequency band. Compared to the previous study, the frequency in Fig.3 is lower, suggesting that frequency jump during the frequency decrease phase is induced by the F_{rw} model. On the other hand, during the frequency increase phase, the effect of F_{rw} is small because the frequency is extremely low. It is found that the behavior during frequency increase can be reproduced by applying a slip model with ω-dependence, as shown in Equation (3). One possible source of externally driven magnetic perturbation is error fields. The τ_v used in both models reproducing the observed behavior during frequency decrease and increase) is approximately consistent with the typical value for JT-60U. It is found that the source of external magnetic perturbation driving the braking force changes during frequency increase and decrease, which caused hysteresis in the JT-60U.

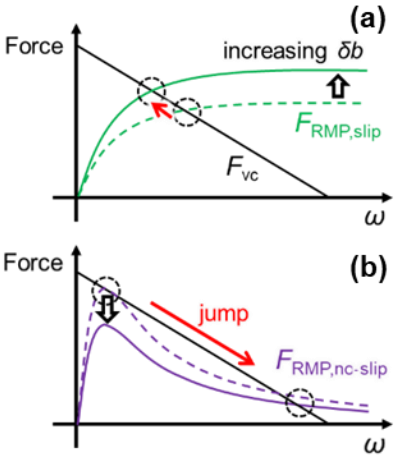

Figure 2. Conceptual diagram of torque balance model (a) with slip, and (b) without slip.

By comparing the physical models of hysteresis obtained from the two devices, it is revealed that the hysteresis of the relationship between frequency and amplitude is caused by the difference in the source of braking force and the frequency range, rather than depending on the type of instability. This finding can contribute to the development of a comprehensive model for the relationship between amplitude and frequency.

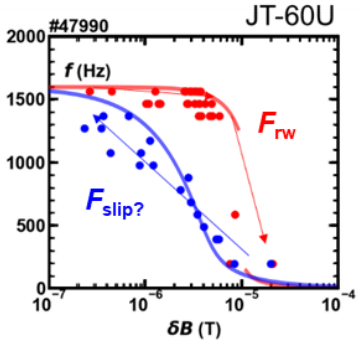

Figure 3. Relationship of amplitude and frequency of the magnetic fluctuation in the JT-60U.

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