Appendix

Resonance Frequency for Displacement and Velocity Resonance

Recall expressions of the magnitude and phase resonanses for the displacement such that

$$A(\omega) = \frac{F_X/M}{\sqrt{({\omega_0}^2 - \omega^2)^2 + k^2\omega^2}} \tag{1}$$

$$\tan\phi(\omega) = \frac{k\omega}{{\omega_0}^2 - \omega^2}, \quad k = R/M = 2\delta_0, \tag{2}$$

for a simple resonator under the sinusoidal external force with magnitude F_X. The magnitude response takes its maximum at the frequency of the external force such that

$$\omega_M = \sqrt{{\omega_0}^2 - \frac{k^2}{2}}, \tag{3}$$

where the denominator becomes the minimum. Note that the resonance frequency is slightly lower than the eigenfrequency ω_0 that is the frequency of the free oscillation. Consequently, the terms resonance and eigenfrequencies should be distinguished[5].

As stated above, the resonance frequency becomes lower as the damping factor increases; however, the phases take $-\pi/2$ at the eigenfrequency independent of the damping factor as shown in Fig. 2.3 in the main text. The phase of the displacement decreases to $-\pi/2$ from the initial phase position 0 through $-\pi/2$.

The resonance frequency, however, differs for the velocity response. The magnitude and phase for the velocity response are given by

$$B(\omega) = \omega A(\omega) = \frac{F_X}{\sqrt{(\frac{K}{\omega} - \omega M)^2 + R^2}} \tag{4}$$

$$\tan\Phi(\omega) = \frac{k\omega}{\omega_0^2 - \omega^2} + \frac{\pi}{2}. \tag{5}$$

The magnitude for the velocity response takes its maximum at the frequency $\omega = \omega_0$ that is equal to the eigenfrequency independent of the damping conditions. Namely, the eigenfrequency is uniquely determined for the vibrating system; however, the resonance frequency depends on the response to be observed. The phase for the velocity response decreases from $\pi/2$ at the initial phase position to $-\pi/2$ through 0 at the resonance frequency, i.e., the eigenfrequency.

Figure 1 shows the magnitude and phase responses for the displacement, velocity, and acceleration. The differences of the magnitude and phase responses are due to the variables to be observed. Only the velocity is in-phase with the external force at the resonance frequency. Note again the resonance frequencies are not unique in general but depend on the quantity to be observed and the damping conditions.

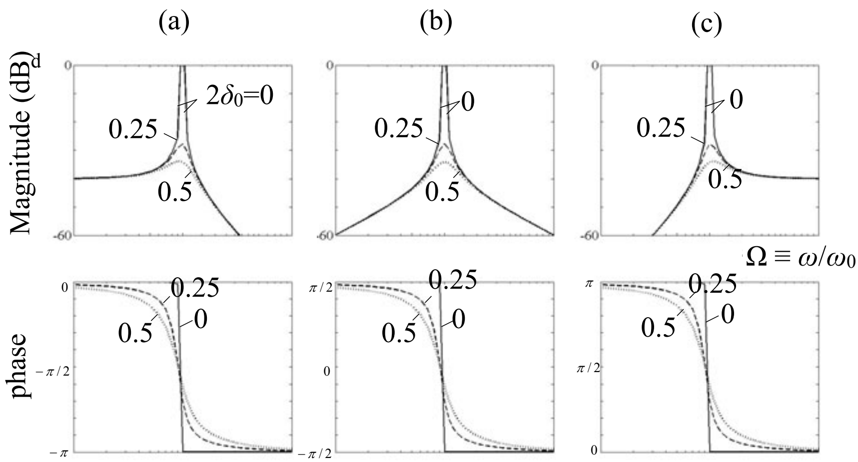

Fig. 1 Magnitude and phase responses for simple oscillator, (a) displacement, (b) velocity, and (c) acceleration

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