

三值噪声调制下电路中的随机共振现象

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摘要: 研究了在三值噪声和热噪声扰动下的 RLC 电路的平均输出幅度增益. 利用随机平均法和 Shapiro-Loginov 公式, 得到了平均输出幅度增益的精确表达式. 通过计算机模拟, 画出了平均输出幅度增益与平坦系数、有噪声和无噪声时, 输出信号振幅与输入信号频率之间的关系曲线. 从结果来看, 系统产生了双值噪声驱动的 RLC 电路中(文献[11])没有的随机共振现象, 甚至还出现了双共振峰.

关键词: 三值噪声; 平均输出幅度增益; RLC 串联电路; 随机共振

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在人们传统的观念中, 噪声是令人厌烦的. 然而, 当在非线性系统中添加一定的噪声后, 系统意外地呈现出了许多非常奇异的现象, 如噪声诱导的相变、输运、共振激活、随机共振等等. 在这些现象例子中, 随机共振的概念是 1981 年, Benzi 等人在研究古气象冰川演化问题时首次提出来的^[1-2]. 此后, 随机共振的理论和实验研究就引起了人们的极大兴趣. 短短的 20 多年间, 发现具有随机共振现象以及利用随机共振现象的系统, 不仅仅出现在物理学领域里, 而且在化学、工程、生物、现代通讯等等领域内已被报道过^[3-18].

早期, 人们认为系统要产生随机共振现象必须具备周期信号、噪声和非线性系统^[1-5]三要素. 而近年的研究表明, 随机共振现象可以出现在具有乘性色噪声或分段噪声驱动的线性系统中^[6-9]. 一般情况下, 人们判断系统是否产生随机共振现象是根据信噪比对噪声参数的非单调依赖关系, 文献[9]和文献[10]就分别研究了波动阻尼参数振子的随机共振及单模激光系统中的随机共振现象. 文献[7]在研究受乘性和加性噪声作用的线性系统的随机共振时, 发现信噪比是乘性噪声相关时间的非单调函数, 此函数关系有最小值出现. 但在电路中幅度增益往往是人们关注的特征量, 因此, 判

断电路系统中, 是否呈现随机共振的依据是幅度增益随噪声参量的变化情况. 文献[11]研究了非对称双值噪声作用下的 RLC 串联电路, 并发现了随机共振现象.

受此文献启发, 笔者采用文献[11]中的 RLC 串联电路模型, 研究在三值噪声^[18]和热噪声共同调制下 RLC 串联电路的随机性质.

1 系统模型

为与文献[11]进行比较, 笔者采用与它类似的 RLC 电路, 因此, 描述系统的微分方程为:

$$LC \frac{d^2 U_0}{dt^2} + LG' \frac{dU_0}{dt} + U_0(t) = U_i(t), \quad (1)$$

式中, $U_i(t) = A_0 \cos(\omega t)$ 是周期激励信号. $G' = 1/R$ 表示电导, 假设电导受到三值噪声的扰动, 即 $G' = G + Z(t)$. 同时系统受到热涨落的影响, 于是(1)式变为:

$$LC \frac{d^2 U_0}{dt^2} + L(G + Z(t)) \frac{dU_0}{dt} + U_0(t) = A_0 \cos(\omega t) + \xi(t), \quad (2)$$

式中, G 是未受扰动时的电导; 内部涨落 $\xi(t)$ 是高斯白噪声, 它的统计特性满足:

$$\langle \xi(t) \rangle = 0, \quad \langle \xi(t) \xi(t') \rangle = 2D\delta(t - t'), \quad (3)$$

式中, D 代表噪声强度. $Z(t)$ 是三值噪声, 它在 $Z_1 = d, Z_2 = 0, Z_3 = -d (d > 0)$ 三值间发生跃迁, 跃迁概率为 ν . 假设其定态概率满足 $P_s(d) = P_s(-d) = q, P_s(0) = 1 - 2q (1/2 > q > 0)$. 而且, 定态时, 三值噪声 $Z(t)$ 满足的统计特征是:

$$\begin{aligned} \langle Z(t) \rangle &= 0, \\ \langle Z(t)Z(t') \rangle &= 2qd^2 \exp\left(-\frac{|t-t'|}{\tau}\right). \end{aligned} \quad (4)$$

转移概率 ν 是噪声关联时间的倒数, 即:

$$\nu = 1/\tau.$$

由于电导不能为负值, 因此对于三值噪声所有态的限制条件为:

$$G > d. \quad (5)$$

2 计算一阶矩

在(2)式中, 令

$$\frac{dU_0(t)}{dt} = x(t), \quad (6)$$

则可得:

$$\begin{aligned} LC \frac{dx(t)}{dt} &= -LGx(t) - LZ(t)x(t) - U_0(t) + \\ &A_0 \cos(\omega t) + \xi(t). \end{aligned} \quad (7)$$

对(6)式和(7)式取系综平均, 得到:

$$\frac{d\langle U_0(t) \rangle}{dt} = \langle x(t) \rangle, \quad (8)$$

$$\begin{aligned} LC \frac{d\langle x(t) \rangle}{dt} &= -LG\langle x(t) \rangle - L\langle Z(t)x(t) \rangle - \\ &\langle U_0(t) \rangle + A_0 \cos(\omega t). \end{aligned} \quad (9)$$

利用 Shaoiro-Loginov 公式^[12]:

$$\begin{aligned} \frac{d\langle Z(t)\Phi(t) \rangle}{dt} &= \langle Z(t) \frac{d\Phi(t)}{dt} \rangle - \\ &\nu \langle Z(t)\Phi(t) \rangle, \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{d\langle Z^2(t)\Phi(t) \rangle}{dt} &= \langle Z^2(t) \frac{d\Phi(t)}{dt} \rangle - 2\nu \cdot \\ &\langle Z^2(t)\Phi(t) \rangle + 2\nu \langle Z^2(t) \rangle \langle \Phi(t) \rangle. \end{aligned} \quad (11)$$

(9)式中的关联因子 $\langle Z(t)x(t) \rangle$ 可写为:

$$\begin{aligned} \frac{d\langle Z(t)x(t) \rangle}{dt} &= \langle Z(t) \frac{dx(t)}{dt} \rangle - \nu \langle Z(t)x(t) \rangle = \\ &-\left(\nu + \frac{G}{C}\right) \langle z(t)x(t) \rangle - \frac{1}{C} \langle Z^2(t)x(t) \rangle - \\ &\frac{1}{LC} \langle Z(t)U_0(t) \rangle. \end{aligned} \quad (12)$$

(12)式中的关联因子 $\langle Z(t)U_0(t) \rangle$ 可写为:

$$\begin{aligned} \frac{d\langle Z(t)x(t) \rangle}{dt} &= \langle Z(t) \frac{dU_0(t)}{dt} \rangle - \\ &\nu \langle Z(t)U_0(t) \rangle = \langle z(t)x(t) \rangle - \\ &\nu \langle Z(t)U_0(t) \rangle. \end{aligned} \quad (13)$$

(12)式中的关联因子 $\langle Z^2(t)x(t) \rangle$ 可写为:

$$\begin{aligned} \frac{d\langle Z^2(t)x(t) \rangle}{dt} &= \langle Z^2(t) \frac{dx(t)}{dt} \rangle - \\ &2\nu \langle Z^2(t)x(t) \rangle + 4qd^2 \nu \langle x(t) \rangle = -(2\nu + \\ &G/C) \langle Z^2(t)x(t) \rangle - \frac{2qd^2}{C} \langle Z(t)x(t) \rangle - \\ &\frac{1}{LC} \langle Z^2(t)U_0(t) \rangle + 4qd^2 \nu \langle x(t) \rangle + \\ &\frac{2qd^2 A_0}{LC} \cos(\omega t). \end{aligned} \quad (14)$$

(14)式中的关联因子 $\langle Z^2(t)U_0(t) \rangle$ 可写为:

$$\begin{aligned} \frac{d\langle Z^2(t)U_0(t) \rangle}{dt} &= \langle Z^2(t) \frac{dU_0(t)}{dt} \rangle - \\ &2\nu \langle Z^2(t)U_0(t) \rangle + 4qd^2 \nu \langle U_0(t) \rangle = \\ &\langle Z^2(t)x(t) \rangle - 2\nu \langle Z^2(t)U_0(t) \rangle + \\ &4qd^2 \nu \langle U_0(t) \rangle. \end{aligned} \quad (15)$$

(8)~(9)式和(12)~(15)式构成 1 组关于 6 个变量

$M_1 = \langle x(t) \rangle, M_2 = \langle U_0(t) \rangle, M_3 = \langle Z(t)x(t) \rangle, M_4 = \langle Z(t)U_0(t) \rangle, M_5 = \langle Z^2(t)x(t) \rangle, M_6 = \langle Z^2(t)U_0(t) \rangle$ 的封闭方程组.

这些方程的通解可写成如下形式:

$$\begin{aligned} M_i &= A_{2i-1} \sin(\omega t) + A_{2i} \cos(\omega t) + \\ &\sum_{j=1}^6 L_{i,j} \exp(\rho_j t). \end{aligned} \quad (16)$$

$L_{i,j} \quad i, j=1, \dots, 6$ 是积分常数, 由初始条件确定. ρ_j 满足下列的多项式方程:

$$\begin{aligned} \rho^6 + d_5 \rho^5 + d_4 \rho^4 + d_3 \rho^3 + d_2 \rho^2 + \\ d_1 \rho + d_0 = 0, \end{aligned} \quad (17)$$

其中,

$$\begin{aligned} d_5 &= 6\nu + 3\frac{G}{C}, \\ d_4 &= 13\nu^2 + 15\frac{G}{C}\nu + 3\left(\frac{G}{C}\right)^2 + \frac{3}{LC} - \frac{2qd^2}{C^2}, \\ d_3 &= 12\nu^3 + 25\frac{G}{C}\nu^2 + \left(\frac{12}{LC} + \frac{G}{C} + 11\frac{G^2}{C^2} - \right. \\ &\left. \frac{10qd^2}{C^2}\right)\nu + \frac{6G}{LC^2} + \frac{G^2}{C^2}\left(1 + \frac{G}{C}\right) - \frac{2qd^2}{C^2}\frac{G}{C}, \end{aligned}$$

$$\begin{aligned}
d_2 &= 4\nu^4 + 16\frac{G}{C}\nu^3 + \left[\frac{17}{LC} + 6\frac{G}{C}\left(1 + \frac{G}{C}\right) - \right. \\
&\quad \left. \frac{8qd^2}{C^2} \right] \nu^2 + \left[\left(\frac{16}{LC} + 9\frac{G}{C} \right) \frac{G}{C} + \right. \\
&\quad \left. 2\left(1 + \frac{2qd^2}{C^2}\right) \frac{G}{C} + \frac{8qd^2}{C^2} \right] \nu + \\
&\quad \left(\frac{2}{LC} + \frac{G}{C} \right) \frac{G^2}{C^2} + \frac{1}{LC} \left(\frac{3}{LC} - \frac{2qd^2}{C^2} \right), \\
d_1 &= 2\left(\frac{2}{LC} + \frac{G}{C} \right) \nu^3 + \left[\frac{1}{LC} \left(1 + \frac{G}{C} \right) + \right. \\
&\quad \left. 2\frac{G}{C} \left(\frac{6}{LC} + 3\frac{G}{C} + \frac{qd^2}{C^2} \right) \right] \nu^2 + \\
&\quad \left[\frac{G}{LC^2} \left(1 + \frac{G}{C} \right) + 2\left(\frac{2}{LC} + \frac{G}{C} \right) \frac{G^2}{C^2} - \right. \\
&\quad \left. \frac{1}{LC} \left(\frac{2}{LC} - \frac{2qd^2}{C^2} \right) \right] \nu + \frac{1}{L^2 C^2} \left(1 + \frac{G}{C} \right), \\
d_0 &= \frac{4}{LC} \nu^4 + \frac{6G}{LC^2} \nu^3 + \frac{2}{LC} \left[\frac{2}{LC} + \right. \\
&\quad \left. \frac{1}{2LC} + \frac{G^2}{C^2} \right] \nu^2 + \frac{3G}{L^2 C^3} \nu + \frac{1}{L^3 C^3}.
\end{aligned}$$

为了保证(16)式解的稳定性,除了(5)式的限制之外,要求 ρ 必须满足负实根的条件.根据劳斯-赫尔维茨判据,得到

$$\begin{aligned}
&d_5 > 0, d_4 > 0, d_3 > 0, d_2 > 0, d_1 > 0, \\
&d_0 > 0, d_4 d_5 > d_3, d_3 d_4 d_5 > d_3^2 + d_2 d_5^2, \\
&(d_2 d_5 - d_1)(d_3 d_4 d_5 - d_3^2 - d_2 d_5^2) > \\
&(d_4 d_5 - d_3)(d_1 d_4 d_5 - d_1 d_3 - d_5^2 d_0), \\
&[(d_2 d_5 - d_1)(d_3 d_4 d_5 - d_3^2 - d_2 d_5^2) -
\end{aligned}$$

$$\begin{aligned}
&(d_4 d_5 - d_3)(d_1 d_4 d_5 - d_1 d_3 - d_5^2 d_0)] \cdot \\
&(d_1 d_4 d_5 - d_1 d_3 - d_5^2 d_0) > \\
&(d_3 d_4 d_5 - d_3^2 - d_5^2 d_2)^2 d_0.
\end{aligned} \quad (18)$$

一阶矩也就是系统平均输出的稳态响应,其可以写为:

$$M_1 = A_1 \sin(\omega t) + A_2 \cos(\omega t), \quad (19)$$

或者是,

$$M_1 = A \sin(\omega t + \phi), \quad (20)$$

其中,

$$A = (A_1^2 + A_2^2)^{\frac{1}{2}}, \quad \phi = \arctg\left(\frac{A_1}{A_2}\right),$$

其中, A 代表输出信号的振幅, ϕ 代表输出信号的相位. A_1, A_2 系数的表达式写在附录中.

由文献[11]的定义可知,该系统平均输出幅度增益为:

$$H = \frac{A}{A_n}, \quad (21)$$

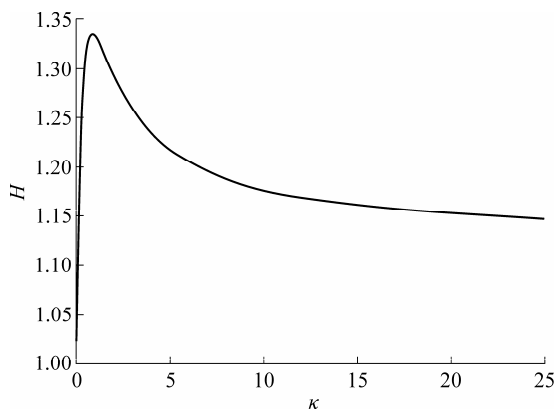
其中,

$$A_n = \frac{A_0}{\sqrt{(1 - LC\omega)^2 + (LG\omega)^2}},$$

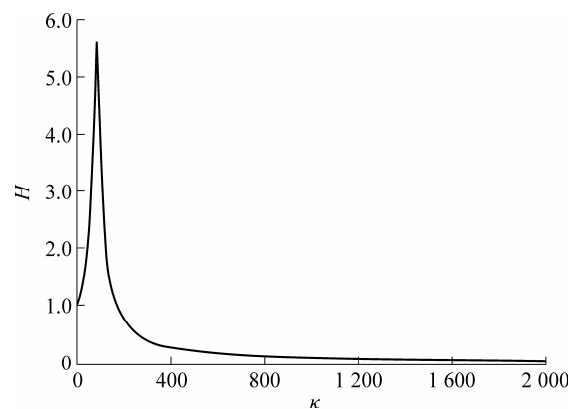
它代表无噪声时系统的输出信号幅度.

3 模拟结果

由(21)式可得出系统的平均输出幅度增益与噪声参量及系统参量之间的变化关系.图1~图3分别绘出了有噪声和无噪声时,平均输出幅度增益 H 与平坦系数 κ 、输出信号振幅与输入信号频率 ω 关系曲线.图中电阻单位为欧姆;电感单位为亨利;电容单位为法拉;电压单位为伏特;其余物理

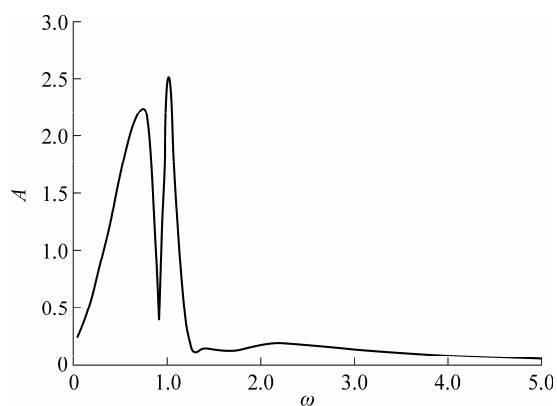
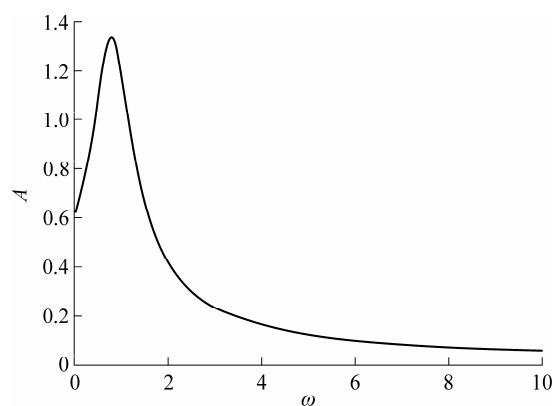
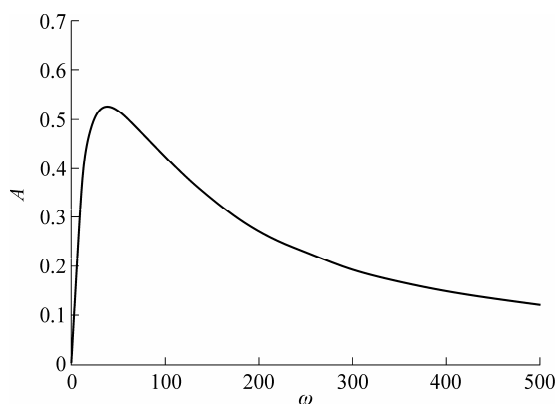
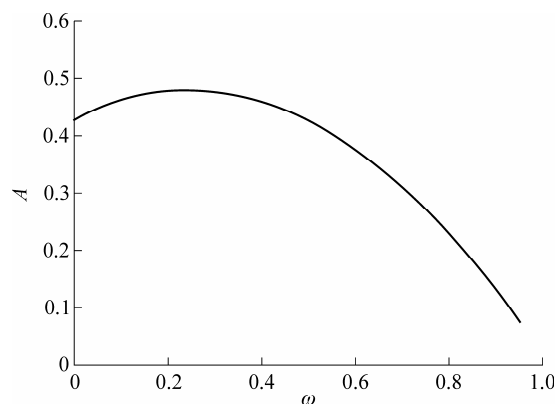


(a) $L=0.5 \text{ H}, C=2 \text{ F}, G=0.1 \text{ S}, \omega=0.9, d^2=0.9, \nu=0.5, A_0=1$



(b) $L=0.1 \text{ H}, C=1 \times 10^{-6} \text{ F}, G=0.1 \text{ S}, \omega=1000, d^2=0.9, \nu=0.005, A_0=1$

图1 平均输出幅度增益 H 与平坦系数 κ 关系曲线

(a) 有噪声时, $L=0.5$ H, $C=2$ F, $G=1$ S, $A_0=0.6$, $2qd^2=0.9$, $\nu=0.5$ (b) 无噪声时, $L=0.5$ H, $C=2$ F, $G=1$ S, $A_0=0.6$ 图 2 输出信号振幅 A 与输入信号频率 ω 间的关系曲线(a) 有噪声时, $L=0.04$ H, $C=1 \times 10^{-6}$ F, $G=0.01$ S, $A_0=0.6$, $2qd^2=0.9$, $\nu=0.005$ (b) 无噪声时, $L=0.04$ H, $C=1 \times 10^{-6}$ F, $G=0.01$ S, $A_0=0.6$ 图 3 输出信号振幅 A 与输入信号频率 ω 间的关系曲线

量的单位为导出单位。

在图 1(a)和图 1(b)中, 可以看到在系统参量及噪声参量取不同值时, 随着噪声平坦系数的增加, 平均输出幅度增益逐渐增加; 在平坦系数达到某个值时, 平均输出幅度增益达到最大值; 此后, 随着噪声平坦系数的增加, 平均输出幅度增益反而逐渐减小。说明随着噪声平坦系数的变化, 平均输出幅度增益出现了峰值, 即系统表现出了随机共振现象。

在图 2(a)和图 2(b)中, 显示了在相同系统参量条件下, 有噪声输入和无噪声输入时, 不同条件下系统输出信号振幅与输入信号频率的关系。从图中可见, 不论有没有噪声, 随着输入信号频率的变化, 在它达到某值时, 系统输出信号振幅都出现了峰值, 说明系统出现了随机共振行为。不同的是, 有噪声时系统表现出的随机共振现象更强烈, 而且出现了 2 个峰值。

在图 3(a)和图 3(b)中, 显示了在相同的系统参量条件下, 有噪声输入和无噪声输入时, 系统输出信号振幅与输入信号频率的关系。与图 2(a)和图 2(b)相比较, 系统的参量完全不同。但从图 3(a)和图 3(b)中可以看到, 不论有没有噪声随着输入信号频率的变化, 在它达到某值时, 系统的输出信号振幅都出现了峰值, 说明系统出现了随机共振行为。不同的是, 有噪声时系统表现出的随机共振现象更强烈。

4 结论

研究了在三值噪声和热噪声扰动下的 RLC 电路的平均输出幅度增益, 从研究结果来看, 在适当的系统参数、激励信号和噪声参数条件下, 平均输出幅度增益表现出了随机共振现象, 甚至出现了双共振峰。

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附录

(1) A_{2i-1}, A_{2i} 系数

$$A_1 = \frac{a_4 c_5 + b_4 c_6}{a_4^2 + b_4^2},$$

$$A_2 = \frac{b_4 c_5 - a_4 c_6}{a_4^2 + b_4^2},$$

$$A_3 = -\omega A_2,$$

$$A_4 = -\omega A_1$$

$$A_5 = a_2 A_1 + b_2 A_2 + c_1,$$

$$A_6 = -b_2 A_1 + a_2 A_2 + c_2,$$

$$A_7 = \left(C\omega^2 - \frac{1}{L} \right) A_1 + G\omega A_2,$$

$$A_8 = -G\omega A_1 + \left(C\omega^2 - \frac{1}{L} \right) A_2 + CA_0,$$

$$A_9 = -a_3 A_1 - b_3 A_2 + c_3,$$

$$A_{10} = b_3 A_1 - a_3 A_2 + c_4,$$

$$A_{11} = b_1 A_5 + a_1 A_6,$$

$$A_{12} = -a_1 A_5 + b_1 A_6,$$

其中,

$$a_1 = C\omega v + C\omega \left(v + \frac{G}{C} \right),$$

$$b_1 = C\omega^2 - C\omega \left(v + \frac{G}{C} \right) - \frac{1}{L},$$

$$a_2 = \frac{v \left(C\omega^2 - \frac{1}{L} \right) - G\omega^2}{\omega^2 + v^2},$$

$$b_2 = \frac{\omega \left(C\omega^2 - \frac{1}{L} \right) + G\omega v}{\omega^2 + v^2},$$

$$a_3 = h_1 a_2 - h_2 b_2 + 2qd^2 L \left(C\omega^2 - \frac{1}{L} \right),$$

$$b_3 = h_1 b_2 + h_2 a_2 + 2qd^2 LG\omega + 4qd^2 LG\omega v,$$

$$a_4 = a_1 a_2 + b_2 b_1 + 2v b_3 - \omega a_3,$$

$$b_4 = a_1 b_2 - a_2 b_1 - 2v a_3 - \omega b_3 - 4qd^2 v,$$

$$c_1 = \frac{\omega C A_0}{\omega^2 + \nu^2},$$

$$c_2 = \frac{\nu C A_0}{\omega^2 + \nu^2}$$

$$c_3 = -h_1 c_1 - h_2 c_2,$$

$$c_4 = h_2 c_1 - h_1 c_2 + 2qd^2 A_0(1 - LC),$$

$$c_5 = b_1 c_2 - a_1 c_1 - 2\nu c_4 - \omega c_3,$$

$$c_6 = b_1 c_1 + a_1 c_2 - 2\nu c_3 + \omega c_4,$$

$$h_1 = LC \left(2\nu + \frac{G}{C} \right) b_1 + LC \omega a_1,$$

$$h_2 = LC \left(2\nu + \frac{G}{C} \right) a_1 - LC \omega b_1.$$

(2) $L_{i,j}$ 的系数

$$L_{1,j} = 1,$$

$$L_{2,j} = \rho_j L_{1,j},$$

$$L_{3,j} = -\frac{C \rho_j \left(\rho_j + \frac{G}{C} \right) + \frac{1}{L}}{\rho_j + \nu} L_{1,j},$$

$$L_{4,j} = -\left[C \rho_j \left(\rho_j + \frac{G}{C} \right) + \frac{1}{L} \right] L_{1,j},$$

$$L_{5,j} = -LC \left[\left(\rho_j + 2\nu + \frac{G}{C} \right) L_{6,j} + \frac{2qd^2}{C} L_{4,j} - 4qd^2 \nu L_{2,j} \right],$$

$$L_{6,j} = -C \left(\rho_j + \nu + \frac{G}{C} \right) L_{4,j} - \frac{1}{L} L_{3,j}.$$

Phenomena of Stochastic Resonance in an RLC Series Circuit Induced by Trichotomous Noise and Gaussian White Noise

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Abstract: This paper studies the phenomena of stochastic resonance in an RLC series circuit induced by trichotomous noise and Gaussian white noise. Based on the random average method and Shapiro-Loginov formula, an explicit expression of the average output amplitude gain (AOAG) is obtained. By simulation, we obtain the curves of AOAG and flatness coefficient, the amplitude of the output signal and the frequency of the input signal under both the noisy and noise-free condition. The results show that the AOAG is a non-monotonic function of flatness coefficient, i.e., the system shows the phenomena of stochastic resonance. In addition, the system shows double-resonance phenomenon which is not reported in Ref. [11].

Key words: trichotomous noise; average output amplitude gain; RLC series circuit; stochastic resonance

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