

Lesson 8 System Design and Compensation Techniques

Control systems are designed to perform specific tasks. The requirements imposed on the control system are usually referred as performance specifications. They generally relate to accuracy, relative stability and speed of response.

Generally, the performance specifications should not be more stringent than necessary to perform the given task. If the accuracy at steady-state operation is of prime importance in a given control system, then we should not require unnecessarily rigid performance specifications on the transient response since such specifications will require expensive components. We should remember that the most important part of control system design is to state the performance specifications precisely so that they will yield an optimal control system for a given purpose.^[1]

In this lesson, we are going to briefly introduce the design and compensation procedure of single-input-single-output (SISO) , linear time-invariant (LTI) control systems by the frequency response and root-locus approaches. Compensation is the modification of the system dynamics to satisfy the given specifications.

Setting the gain is the first step in adjusting the system for satisfactory performance. In many cases, increasing the gain value will improve the steady-state behavior but will result in poor stability or even instability. Then it is necessary to redesign the system (by modifying the structure or by incorporating additional devices or components) to alter the overall behavior so that the system will behave as desired.

Fig. 8.1 shows the configuration where the compensator $G_c(s)$ is placed in series with the plant. This scheme is called series compensation. Another kind of compensation is feedback compensation. Generally, series compensation may be simpler than feedback compensation.

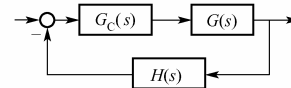


Fig. 8.1 Series compensation

In discussing compensators, we frequently use terminology as lead network, lag network, and lag-lead network. If a sinusoidal input e_i is applied to the input of a network and the steady-state output e_o (which is also sinusoidal) has a phase lead, then the network is called a lead network. Similarly, if the steady-state output e_o has a phase lag, then the network is called a lag network. In a lag-lead network, phase lag and phase lead both occur in the output but in different frequency regions; phase lag occurs in the low-frequency region and phase lead occurs in the high-frequency region.

Root-locus approach to control system design

The root-locus method is a graphical method for determining the locations of all closed-loop poles from knowledge of the locations of the open-loop poles and zeros as some parameter (usually the gain) is varied from zero to infinity. The method yields a clear indication of the effects of parameter adjustment. In practice, the root-locus plot of a system may indicate that the desired performance cannot be achieved just by the adjustment of gain. Then it is necessary to reshape the root loci to meet the performance specifications.

In designing a control system, we may modify the original root loci by inserting a suitable compensator $G_c(s)$ (as shown in Fig.8.1). Once the effects on the root locus of the addition of the poles and/or zeros are fully understood, we can readily determine the locations of the pole(s) and zero(s) of the compensator that will reshape the root locus as desired.^[2] In the design by the root-locus method, the root-loci of the system are reshaped through the use of a compensator so that a pair of dominant closed-loop poles can be placed at the desired locations. (Usually, the damping ratio and undamped natural frequency may be specified by the locations of a pair of dominant closed-loop poles.)^[3]

The addition of a pole to the open-loop transfer function has the effect of pulling the root locus to the right, tending to lower the system's relative stability and to slow down the settling of the response.^[4] The addition of a zero has the effect of pulling the root locus to the left, tending to make the system more stable and to speed up the settling of the response.

The root-locus approach to design is very powerful when the specifications are given in terms of time domain quantities, such as the damping ratio and undamped natural frequency, maximum overshoot, rise time and settling time.

Let us consider a design problem. The original system either is unstable for all values of gain or is stable but has undesirable transient response characteristics. In this case, the reshaping of the root locus is necessary in order that the dominant closed-loop poles be at desired locations in the complex plane. Inserting an appropriate lead compensator in cascade with the feed-forward transfer function may solve this problem.^[5]

Frequency-response approach to control system design

It is important to note that in a control system design, transient-response performance is usually most important. In the frequency-response approach, we specify the transient-response in terms of the phase and gain margin, resonant peak magnitude, the gain crossover frequency, resonant frequency and bandwidth.^[6] Although the correlation between the transient response and frequency response is indirect, the frequency domain specification can be met conveniently by means of Bode diagram.

Design in the frequency domain is simple and straightforward. After the open loop has been

designed by frequency response method, the closed loop poles and zeros can be determined. The transient response characteristics must be checked to see whether the designed system meets the requirements in the time domain. If it does not, the compensator has to be modified and the analysis must be repeated until a satisfactory result is obtained.

Basically, there are two approaches in the frequency-domain design. One is the polar plot approach and the other is the Bode diagram approach. It is more convenient to work with Bode diagram. A Bode diagram of the compensator can be simply added to the original Bode diagram, and thus plotting the complete Bode diagram is a simple matter.^[7] Also, if the open loop gain is varied, the magnitude curve is shifted up or down without changing the slope of the curve, and the phase curve remains the same.

A common approach to the Bode diagram is that we first adjust the open loop gain so that the requirement on the steady state accuracy is met. Then we plot the magnitude and phase curves of the uncompensated open loop. If the specification on the phase margin and gain margin are not satisfied, then a suitable compensator that will reshape the open loop transfer function is determined.

In many practical cases, compensation is essentially a compromise between steady-state accuracy and relative stability. In order to have a high value of the velocity error constant and yet satisfactory relative stability, we find it necessary to reshape the open loop frequency response curve. The gain in the low-frequency region should be large enough to satisfy the steady-state accuracy requirements. For the medium-frequency region (near the gain crossover frequency ω_c from both directions), the slope of the log-magnitude curve in the Bode diagram should be -20 dB per decade.^[8] This slope should extend over a sufficient wide frequency band to assure a proper phase margin. For the high-frequency region, the gain should be attenuated as rapidly as possible to minimize the effects of noise.

The basic characteristics of lead, lag, and lag-lead compensation are as following. Lead compensation essentially yields an appreciable improvement in transient response and a small change in steady-state accuracy. It may accentuate high-frequency noise effects. On the other hand, lag compensation yields an appreciable improvement in steady-state accuracy at the expense of increasing the transient-response time. Lag compensation will suppress the effects of high-frequency noise signals. Lag-lead compensation combines the characteristics of both lead compensation and lag compensation.

New Words and Phrases

1. compensation [kɒmpen'seɪʃən]	n.	补偿, 调整, 校正
2. impose [ɪm'pəʊz]	v.	将……强加于, 施加, 使……负担
3. stringent ['strɪndʒənt]	adj.	严厉的, 迫切的
4. root-locus ['ru:t-'ləʊkəs]	n.	(pl. root-loci) 根轨迹
5. indication [ɪndɪ'keɪʃən]	n.	指示, 指出, 显示, 暗示
6. transient ['trænzɪənt]	adj.	暂态的, 瞬时的, 过渡过程的

7. magnitude ['mægnɪtju:d]	n.	量值, 幅度
8. straightforward [streɪt'fɔ:wəd]	adj.	直截了当的
9. accentuate [æk'sentʃueɪt]	v.	加强, 强调
10. attenuate [ə'tenʃueɪt]	v.	削弱
11. approach [ə'prəʊtʃ]	n.	方法, 途径
12. characteristic [ˌkærɪktə'rɪstɪk]	n.	特性, 特征
	adj.	特有的, 典型的
13. prime [praɪm]	n.	最初, 青春, 精华
	adj.	主要的, 最初的, 有活力的, 最好的, 根本的, 素数的
14. rigid ['rɪdʒɪd]	adj.	刚硬的, 刚性的, 严格的, 坚硬的, 僵直的, 坚决的, 固定的
15. transient response		暂态响应, 过渡反应, 瞬时 [瞬态] 反应, 瞬时反应特性, 瞬时特性
16. yield [ji:lɪd]	vt.	出产, 产生, 生长, 生产 vi.(~to) 屈服, 屈从, 放弃
	n.	产量, 收益
17. time-domain		时域的
18. overshoot ['əʊvə'ʃu:t]	vt.	打过头, 飞过目标, 超过, 越过
	vi.	射击越标, 行动过火
	n.	超调量
19. settling time		调整时间
20. phase margin		相位裕量
21. gain margin		增益裕度
22. resonant ['rezənənt]	adj.	(引起)共鸣的, 响亮的, 共振的, 深沉的
23. perk [pɜ:k]	vi.	昂首, 恢复, 振作
	vt.	竖起, 打扮
24. resonant perk value		谐振峰值
25. bandwidth ['bændwɪθ]	n.	带宽, 频带宽度

Notes

[1] We should remember that the most important part of control system design is to state the performance specifications precisely so that they will yield an optimal control system for a given purpose.

我们应该牢记, 控制系统设计过程中最重要的一个环节就是把性能要求精确地表达出来, 这样才会设计出对于给定的目的而言最优的控制系统。

本句的结构比较复杂。在 remember 后面 that 所引导的从句是宾语从句, 在该从句中 “to state...” 是从句中的表语从句。在翻译这种英语长句时, 不能够拘泥于原句的语法结

构，而应该在充分理解该语句意思的基础之上，重新组织，再用通顺的汉语表达出来。如果过分拘泥于原来的语法结构，则翻译出来的汉语不通顺。科技英语翻译就是要在尽可能忠实于原文的基础上，将通顺的英语(或汉语)所表达的意思转换成用通顺的汉语(或英语)表达。

[2] Once the effects on the root locus of the addition of the poles and/or zeros are fully understood, we can readily determine the locations of the pole(s) and zero(s) of the compensator that will reshape the root locus as desired.

一旦我们完全理解了增加极点和/或零点对于根轨迹的影响，我们就可以很方便地确定补偿器零点和极点的位置，以使得根轨迹改变成为我们所希望的形状。

Once 引导条件状语从句，而且该条件状语从句是用被动语态。Compensator 后面的 that...引导定语从句修饰 the pole(s) and zero(s) of the compensator。

[3] In the design by the root-locus method, the root-loci of the system are reshaped through the use of a compensator so that a pair of dominant closed-loop poles can be placed at the desired locations. (Usually, the damping ratio and undamped natural frequency may be specified by the locations of a pair of dominant closed-loop poles.)

在用根轨迹法设计的过程中，通过使用补偿器改变系统根轨迹的形状，以使闭环系统一对主导极点位于理想的位置。(通常，阻尼比和无阻尼自然振荡频率是由闭环系统一对主导极点的位置确定的。)

本句中有两个状语，In the design by...介词短语作状语表示场合；而 so that a pair of...状语从句表示结果。

[4] The addition of a pole to the open-loop transfer function has the effect of pulling the root locus to the right, tending to lower the system's relative stability and to slow down the settling of the response.

在开环传递函数中增加一个极点的效果是把根轨迹向右推，倾向于降低系统的相对稳定性，并且降低系统的收敛速度。

介词短语 The addition of a pole to the open-loop transfer function 是句子的主语，现在分词短语 tending to lower...作状语，表示伴随状态。

[5] Inserting an appropriate lead compensator in cascade with the feed-forward transfer function may solve this problem.

在前向传递函数中串联插入一个适当的超前补偿器，就可以解决这个问题。

动名词短语 Inserting an...是句子的主语。

[6] In the frequency-response approach, we specify the transient-response in terms of the phase and gain margin, resonant peak magnitude, the gain crossover frequency, resonant frequency and bandwidth.

在频率响应法中，我们以相位裕量及增益裕量、谐振峰值幅度、增益穿越频率、谐振频率和带宽来表征暂态响应。

在这个句子中，the phase and gain margin, resonant peak magnitude, the gain crossover frequency, resonant frequency and bandwidth 并列成为介词短语 in terms of 后面的宾语。

[7] A Bode diagram of the compensator can be simply added to the original Bode diagram,

and thus plotting the complete Bode diagram is a simple matter.

补偿器的伯德图可以简单地加在原伯德图上, 因此画完整的伯德图是很简单的事。

句子中 and thus plotting... 是一个并列句, 其中动名词短语 plotting the complete Bode diagram 作主语。

[8] For the medium-frequency region (near the gain crossover frequency ω_c from both directions), the slope of the log-magnitude curve in the Bode diagram should be -20 dB per decade.

在中频段(靠近幅频曲线的穿越频率 ω_c 的两边), 在伯德图中对数幅值曲线的斜率应该为 -20 dB/dec。

本句中括号内的部分是介词短语作为定语, 用来修饰 region。

Translating Skills 数词的译法

在专业英语中, 数词出现的频率很高, 对数词的翻译及读法的掌握程度会影响对专业的学习、研究及交流。现分别介绍一些专业英语中常用的数词的译法和数学符号、公式的读法。

1. 基数词的译法和读法

(1) 从 1 到 12 是单个单词:	十一	11 eleven	十二	12 twelve
(2) 从 13 到 19 加后缀 -teen:	十三	13 thirteen	十九	19 nineteen
(3) 从 20 到 90 加后缀 -ty:	二十	20 twenty	二十三	23 twenty-three
	九十	90 ninety		

百位数以上:

五百	500 five hundred
五百六十一	561 five hundred (and) sixty-one
五千六百六十一	5,661 five thousand six hundred (and) sixty-one

2. 序数词的译法和读法

序数词翻译时加“第……”, 如 twelfth 12th 第十二 thirtieth 30th 第三十

3. 数词的增加和减少的译法和读法

(1) The oxygen atom is nearly **16 times heavier than** the hydrogen atom.

氧原子的重量几乎是氢原子的 **16 倍**。(如果把 16 用 n 代替, 常译作“是……的 n 倍, 或“比……(大、多、长) $n-1$ 倍”)

(2) The diode produces **5 times more radiant power than** that one.

这只二极管的辐射功率比那只 **大 4 倍**(是那只的 5 倍)(同上)。

(3) The wire is **twice as long as** that one.

这根电线的长度是那根的 **两倍**。(如果把 twice 用 n 代替, 常译作“是……的 n 倍, 或“比……(大、多、长) $n-1$ 倍”)

(4) The production of air-conditioners has **increased three times** this year.

今年空调的产量增加 2 倍(增加到 3 倍)。(如果句中 three 用 n 表示, 那么常译成“增加了 $n-1$ 倍或增加到 n 倍”)

(5) The production of air-conditioners **has increased by three times** over the previous year.
今年空调的产量比上一年**增加了 3 倍。**

(6) The production of air-conditioners **has decreased by three times** over the previous year.
今年空调的产量比上一年**减少了 3 倍。**

(7) The production of air-conditioners **has increased to three times** this year.
今年空调的产量**增加到了 3 倍。**

(8) The production of air-conditioners **has increased by a factor of three times** this year.
今年空调的产量增加 2 倍。(如果句中 three 用 n 表示, 那么常译成“增加了 $n-1$ 倍”
类似减少的译法有:

(1) reduce by 10% 减少了 10%

(2) reduce to 10% 减少到 10%

(3) reduce by a factor of 10 减少了 9/10(减少到 1/10)

(4) reduce 10 times 减少到 1/10(减少了 9/10)

4. 分数、小数、时间等的译法和读法

(1) 简单的分数。

1/7	七分之一	one seventh	3/4	四分之三	three quarters
1/4	四分之一	a/one quarter	1/2	二分之一	a/one half
$4\frac{1}{2}$	四又二分之一	four and a half	$3\frac{4}{5}$	三又五分之四	three and four-fifths

(2) 复杂的分数。

24/9	九分之二十四	twenty-four over nine
20/83	八十三分之二十	twenty over eight three (twenty eighty-thirds)
7/20	二十分之七	seven twentieths
67/200	二百分之六十七	sixty-seven two hundredths

(3) 小数。

0.124	零点一二四	(nought) point one two four
0.24	零点二四	(nought) point two four
0.4	零点四	(nought) point four
16.789	十六点七八九	one six point seven eight nine

(4) 时间或其他。

60 年代初期	in the early sixties
本世纪 90 年代	in the nineties of the century
20 世纪 90 年代(1990s, 1990's)	nineteen nineties
2005 年 10 月 10 日	October 10th, 2005 (10 th October, 2005/ October 10, 2005/ 10 October 2005)

Fig.7

图 7(直译)

14'59.38"十五分五十九点三八秒 fourteen minutes fifty-nine point three eight seconds

5. 数学符号、公式的读法

+	加(上)	plus/and
-	减(去)	minus
×	乘以	times; multiplied by
÷	除以	divided by/divided
=	等于	is equal to>equals
≈	大约等于	is approximately equal to
()	圆括号	round brackets/parentheses
[]	方括号	squared brackets
/	斜杠	slash
65%	百分之六十五	65 percent
10^9	十的九次方	the ninth power of ten/ten to the power nine/ten to the ninth power
10^{-5}	十的负五次方	ten to the minus five
x'		x prime
x''		x second prime
x_e		x sub e
$\sqrt{2}$	根号 2	the square root of 2
\geq	大于或等于	is more than or equal to
\leq	小于或等于	is less than or equal to
$>$	大于	is more than
δ		delta
Φ		Phi
Ω		omega
ε		epsilon
\propto	与……成比例	varies as/ is proportional to
ω		omega
5 mm	5 毫米	5 millimeters
$x \rightarrow \infty$		x approaches to infinity

Exercises

1. Translate the following into Chinese.

(1) Generally, we should adopt reasonable performance specifications while we are designing a control system.

(2) We often use lead network, lag network, or lag-lead network to work as compensators in control system compensation.

(3) Compensation for a closed-loop control system is essentially a compromise between steady-state accuracy and relative stability of the system.

- (4) The substance reacts three times as fast as the other one.
- (5) The students who take part in physical activities have increased to 10,000.
- (6) One in five women born in 1970 has suffered from depression and anxiety in their thirties, twice the rate of those born in 1940, the University of London has found.

2. Translate the following into English.

- (1) 使用根轨迹法设计控制系统补偿器，就是为了使闭环系统的一对主导极点位于左半 S 平面中的理想位置。
- (2) 超前补偿可以明显改善控制系统的暂态响应，对稳态精度没有影响。
- (3) 用伯德图设计的常用方法是，我们首先调节开环增益，以使稳态精度的要求得到满足。
- (4) 那位警察要了比平常多一倍的罚款。
- (5) 去年钢产量减少了 20%。
- (6) 这家造纸厂的产量比 1980 年增加两倍。

Reading Material An Eye on Reactor and Computer Control

A nuclear power plant operator stared at the computer screen and yawned. As the end of a long shift approached, he was feeling very tired as he looked at icons of pumps, pipes, and turbines. Even so, it was still early in the reactor startup sequence. When an indication that the reactor had gone critical appeared on the screen, the operator tried to rouse himself. There was no need for him or anyone else to be alarmed, however. Based on the way the operator looked at the screen, the computer had already sensed that he was tiring and had begun to assist the operator in reactor control. The computer zoomed in on the displays the operator needed to monitor reactivity and highlighted the important data. It would even be capable of assuming partial reactor control if necessary.

At a research laboratory, a cognitive scientist put a diskette in her computer and studied the screen. The data indicated that a reactor operator had been glancing at a number of widely scattered points in a short time on the computer screen in the reactor control room. "All these eye movements," said the scientist, "tell me the operator is experiencing excessive mental work load. It seems that several displays associated with reactor control must be redesigned to make it easier for the operator to understand quickly what's going on."

A teenager who lost the use of both hands as a result of an automobile accident had found a way to write again. His father bought him an "eye typewriter"—a computer that displays and prints letters from a display of the alphabet on the screen in the order in which they are stared at. The boy enjoyed his ability to control a computer simply by looking at it.

These futuristic scenarios suggest that information on eye gazes—the way people look at an object—can be put to use to determine a person's mental work load and level of fatigue, to guide the design of computer displays to speed human processing of information, and to control

computers. Other applications include controlling camera positions on robots and guiding an artificial intelligence system in recognizing enemy targets.

At ORNL computer software has been developed to make possible an improved eye-gaze measurement technology. Such an innovation could be the basis for advanced eye-gaze systems that may have applications such as those mentioned above.

New Words and Phrases

1. yawn [jɔ:n]	v. n.	打哈欠, 哈欠
2. turbine ['tɜ:bin]	n.	涡轮机
3. critical ['kritikəl]	adj.	危急的, 临界的
4. scatter ['skætə]	v.	分散, 散开, 驱散
5. innovation [ˌɪnəʊ'veɪʃən]	n.	改革, 创新
6. zoom in		(镜头)放大