Professional training of Engineer on system Dynamics

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ABSTRACT

In this paper a professional training schedule on system dynamics for engineers is discussed on the basis of ten years teaching and training practice.
Three main parts are considered in detail. These are theory, practice, and final performance test. All examples included are to meet the specific necessity of engineers, and are coming from practical problems.
An overall block diagram of Training is presented. Practice shows this schedule is efficient and attractive.

1. INTRODUCTION

High technique development calls for high potential managers and engineers, not only to meet production reqirements such as model of quality control, sales price prediction, decision of upgrading products, etc, but also to bridge the gap between theoretical achievements and new technology creation. In this case for most engineering areas, system dynamics plays an important role, e. g. robotics, signal processing, CNC technique, power plant control, traffic management etc.
In order to fit different requirements, five main courses are selected for general, these are: Linear system, Nonlinear system, Optimization and Optimal control, signal processing, and System Identification. Besides, special topics such as information acquisition, estimation theory, philosophical method, fussy control etc. are inserted optionally as the implemental tutorial.

2. THEORY TEACHING

Engineers in the duration of service are mainly working on practical problems, and have accumulated a lot of questions relating to system dynamics. This is because in the real world every part must belong to some "running" system, and a lot of system factor, state or parameters have to be evaluated or controlled in dynamic situation. According to the report from Enterprise Community in China most engineers need the help of related theory. But the schedule of theory teaching hinges on a central problem: how to modify the conventional plan for students and create an optimal new routine for engineers. Many educators are finally coming to realize that "concepts, tools, and practice" is the best answer. Following this the kernel portion of theory teaching is divided into four parts, these are:

a. Fundamental theory and its academic concept;
b. Engineering practical example for demonstration;
c. Applied computer programs learning;
d. Problem discussion and solving.

The key points of this arrangement can be summarized as follows:

a. Engineers have to master theories and concepts, even in mathematics. The specific condition here is that they also have to collect a lot of intuitive examples to enhance the relation between theory and practice;

b. The advent of computer aids the realization of recent advances in theory. A large number of CAD/CAM/CAE applied software package links concept and engineer application. Engineers are infinitely better equipped to learn them when they have mastered a few theories or concepts.

c. For engineers, "To touch over with to think, observation more than books, experience rather than persons", are the prime principles of training. If the applied theories and concepts tie in properly with engineering application. In the case practice always induces their creative idea and reinforces their theoretical understanding in a mode of "positive feedback".

d. The four parts are internally connected and mutually affecting each other. But how to match them in a proper ratio is still a problem left.

In order to fit the special need for engineers along with explanation of theories aditional effective methods of teaching are incoperated. They are listed in the following paragraphs. The criteria is "easy to understand, more to get, flexible to manipulate".

A. Physical understanding

One strong point of engineer is to form idea with physical comprehension, so if theory teaching combines with physical explanation they will easily grasp the spirit. In this case a better way is to rewrite the conventional text, with more qualitative interpretation. An example is the physical explanation of Kalman filter equation set for linear time invariant discrete system. The system equations are:

$$X_{k+1}=F_kX_k+G_kW_k \quad (1.1)$$

$$Z_k=H_kX_k+V_k \quad (1.2)$$

where

X_k—state vector

Z_k—output vector

W_k, V_k,—independent white noise of system and of measure with zero means

$E[V_k, V_l^T]=R_k\delta_{kl}$

$E[W_k, W_l^T]=Q_k\delta_{kl}$

δ_{kl}—kronecker delta, which is 1 for k=l and 0 otherwise.

The Kalman filter equation comprises the system are as follows:

* main equation

$$\hat{X}_k=F_{k/k-1}\hat{X}_{k-1}+K_k(Z_k-H_kF_{k/k-1}\hat{X}_{k-1}) \quad (1.3)$$

* gain equation

$$K_k=P_{k/k-1}H_k^T(H_kP_{k/k-1}H_k^T+R_k)^{-1} \quad (1.4)$$

* one step prediction equation

$$\hat{X}_{k/k-1}=F_{k/k-1}\hat{X}_{k-1} \quad (1.5)$$

* covariance equation

$$P_{k/k-1}=F_{k/k-1}P_{k-1}F_{k/k-1}^T+G_{k-1}Q_{k-1}G_{k-1}^T \quad (1.6)$$

* update covariance equation

$$P_k=(1-K_kH_k)P_{k/k-1}(1-H_kK_k)^T+K_kR_kK_k^T \quad (1.7)$$

where X——estimatied state

P——covariance matrix

In the following paragraphs a number of physical properties of kalman filter are listed both in general description and in individual terms.

A-1. General description

(a) Kalman filter is a state estimator the results of estimation should contain two terms, X——state estimated;

P——covariance showing the error range.

it is the same as the nominal dimension and the tolerance in measurement.

(b) Kalman filter is a step by step process, the occasion of step change is due to the appearance of Z_i, as shown in Fig. 2-1.

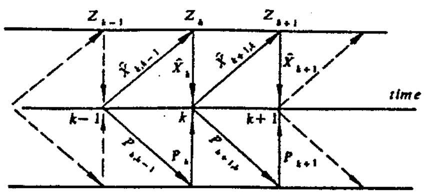

Fig. 2-1

So Z_k is the major information. In equation (1.3) $H_k F_{k/k-1} \hat{X}_{k-1}$ is the computed output, Z_k is the real output, the difference is called "innovation" used for modification of $\hat{X}_{k-1}$. Also before attedance of Z_k estimation belongs to prior conditional probability problem otherwise posterior. The reason of using recursive step by step algorithm is due to the on-line operation and memory saving.

(c) Kalman filter exits mainly because measure noise V_i exits.

Suppose $[V]=[0]$, $[H]$ full rank, $[P]$ positive definite, then equation (1,4) changes to

$$K_k = H_k^{-1} \quad (1.8)$$

and

$$\hat{X}_k = F_{k/k-1}\hat{X}_{k-1} + H_k^T (Z_k - H_k F_{k/k-1} \cdot \hat{X}_{k-1}) = H_k^{-1} Z_k = X_k \quad (1.9)$$

$$P_k = (I - K_k H_k) P_{k/k-1} (I - K_k H_k)^T + K_k R_k K_k^T = 0 \quad (1.10)$$

It implies if the measurement is exact there is no need using Kalman filter.

(d) The main function set of Kalman filter are essentially deduced from the output equation.

Suppose

$$Z = H_x + V \quad (1.11)$$

$$X \sim N(u,p), \quad V \sim N(0,R)$$

they are mutually independent, then it is easy to prove

$$E(X|Z) = \mu + P_x H^T (HP_x H^T + R)^{-1} (Z - H\mu) \quad (1.12)$$

$$Var(X|Z) = P_x - P_x H^T (HP_x H^T + R)^{-1} HP_x \quad (1.13)$$

they have probably the similar structures as the Kalman filter equations.

A-2. Remarks about some individual terms

(a) The main equation (1.3) is a kind of typical Ttructure of linear recursive Algorithm. From (1.3) easy to see $\hat{X}_k$ is a linear combination of former estimated state $\hat{X}_{k-1}$ and observed value Z_k. If comparing it with the equation of recursive averaging, a probably similar structure emerges.

take $X = [x_1, x_2, \cdots, x_n]$

the average value

$$\bar{X}_n = \frac{1}{n} \sum_{i=1}^{n} X_i \quad (2.1)$$

and

$$\bar{X}_{n+1} = \frac{1}{n+1} \sum_{i=1}^{n+1} X_i = \bar{X}_n + \frac{1}{n+1} (X_{n+1} - \bar{X}_n) \quad (2.2)$$

here X_{n+1} is the new data same as Z_k. The difference is that the Kalman filter is a dynamic system, but the later is a stationary.

(b) Gain matrix K_k is a measure of the covariance ratio.

From equation (1.4)

$$K_k = P_{k/k-1} H_k^T (H_k P_{k/k-1} H_k^T + R_k)^{-1}$$

or

$$K_k = P_k H_k^T R_k^{-1} \quad (2.3)$$

without loss of generality

take $H_k = [I]$

$$R_k=\begin{bmatrix}\sigma_1^2 & \cdots & & 0\\ & \sigma_2^2 & \ddots & \\ 0 & \cdots & & \sigma_n^2\end{bmatrix} \tag{2.4}$$

$$P_k=\begin{bmatrix}P_{11} & P_{12} & \cdots & P_{1n}\\ P_{21} & P_{22} & \cdots & P_{2n}\\ \cdots & \cdots & \cdots & \cdots\\ P_{n1} & P_{n2} & \cdots & P_{nn}\end{bmatrix} \tag{2.5}$$

then

$$K_k=\begin{bmatrix}P_{11}/\sigma_1^2 & P_{12}/\sigma_2^2 & \cdots & P_{1n}/\sigma_n^2\\ P_{21}/\sigma_1^2 & P_{22}/\sigma_2^2 & \cdots & P_{2n}/\sigma_n^2\\ \cdots & \cdots & \cdots & \cdots\\ P_{n1}/\sigma_1^2 & P_{n2}/\sigma_2^2 & \cdots & P_{nn}/\sigma_n^2\end{bmatrix} \tag{2.6}$$

It shows some definite and relative behaviors between these two uncertainties. More intuitively, when Q_k grows, K_k also goes up, but when R_k grows, K_k goes down, it means the information from Z_k is less believable.

(c) Covariance matrix P_k is a measure of the optimality of state estimation. P_k is an overall comprehensive term, consisting three main error sources P_0, R_k, Q_k coming through different transfer routine F_k, G_k, H_k. Norm of P_k means the width of error band of state estimation. The lower the norm value the better the estimated Value X. No matter what the initial P_0 selected P_k will reach a definite $\bar{P}$ at last.

One interesting question is: why P_k does not directly deal with Z_k? The statistical reason is that any one measured value can not change the overall comprehensive property of the system.

(d) R, Q are prior statistical values, it can be obtained either from test or directly from the company catalog. Anyway matrix R is demanded to be positive definite. In order to force positive definite of $(H_kP_{k/k+1}H_k^T+R_k)$ for inverse operation. In practice the upper limit of R should be chosen because of mathematical model with error or unpredictable system disturbance. Usually the dimension of R is less or equal to the dimension of state X, it implies some state output value can not be measured. In this case Kalman filter is also valid if the system noise is less heavy.

B. Example Demonstration

T. Jefferson [* 1] said: "… more honorable and more profitable, too, to set a good example than to follow a bad one". Examples exist in most books. The emphasis here is focused on how to select property examples concerning both theory and engineering practice.

For demonstration of model formulation some engineering real problems are used to show the whole procedure. An example is an assembly process as depicted in Fig. 2-2

where 1——steel bush

2——massive aluminum body

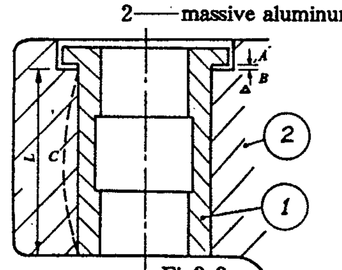

Fig2-2

Before assembly part 1 is soaked in liquid hydrogen to −150℃; and part 2 is put in constant temperature oven to +150℃.

After assembly surface A and B are closely contacted together in the beginning, but in the last with no exception clearance Δ happens. For revealing the mechanism of this phenomena mathematical model formulation on principles of system dynamics is necessary. Suppose part 1 and part 2 are pulled out from their original temperature situation to room temperature (20℃) separately at time t_0. Then the time history of these processes is shown in Fig. 2—3 as line 1 and line 2. The line 1—2 means part 1 is put into part 2 in assembly form.

For curve 2 the mathematical model is

$$T_2\frac{dy_2}{dt}+K_2y_2=20, \qquad y_2(0)=150 \qquad (2.7)$$

T_2——time constant for part 2,

Suppose the temperature change of part 2 is not affected by part 1 due to its large heat capacity. Then the curve 1-2 can be written as

$$T_1\frac{dy_1}{dt}+k_1y_1=y_2(t), y_1(0)=-150 \qquad (2.8)$$

$$y_1(t)=\frac{20}{k_1k_2}+\frac{(150K_2-20)T_2}{(k_1T_2-K_2T_1)k_2}e^{-\frac{k_2}{T_2}t}-\left[150+\frac{20}{K_1K_2}+\frac{(150K_2-20)T_2}{(K_1T_2-K_2T_1)K_2}\right]e^{-\frac{K_1}{T_1}t} \qquad (2.9)$$

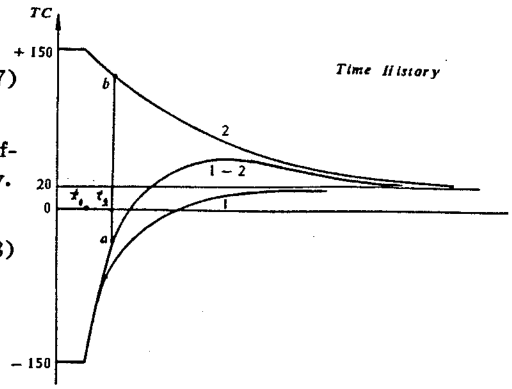

Fig 2-3

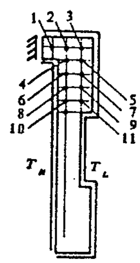

Fig. 2-4

T_1, T_2 can either measured or calculated. Another related problem is about the shape deformation of part 1 due to the temperature gradient field. In order to determine the specific point c of contact during the heat transfer dynamical process, for simplification take a thin slice of part 1 as shown in Fig. 2-4. The boundary condition are TH and TL, which means the high and low temperature. This field problem can be approximated by a series of difference equations involving the magnitudes of required variable at the mesh points. The difference equation corresponding to Laplace' s equation is based on the heat balance principle i. e. temperature at any point is equal to the average value of the temperatures at the four neighbouring points.

$$\begin{aligned}
T_1&=1/4[T_1+T_2+T_H+T_L]\\
T_2&=1/4[T_1+T_3+T_4+T_L]\\
&\cdots\cdots\\
T_8&=1/4[T_6+T_9+T_{10}+T_L]\\
T_9&=1/4[T_7+T_8+T_L+T_L]\\
&\cdots\cdots
\end{aligned} \qquad (2.10)$$

rewrite it in matrix from, as

$$\begin{bmatrix}
3 & -1 & & & & & & \\
-1 & 4 & -1 & -1 & & & & \\
 & & & \ddots & & & & \\
 & & -1 & & 4 & -1 & -1 & \\
 & & & -1 & -1 & 4 & & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\end{bmatrix}
\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_8 \\ T_9 \\ \vdots \end{bmatrix}
=
\begin{bmatrix} T_H+T_L \\ T_L \\ \vdots \\ \vdots \\ \vdots \\ T_L \\ 2T_L \\ \vdots \end{bmatrix} \qquad (2.11)$$

solve it, the temperature gradient gives that the bush part 1 deformation is probably along the dash line as shown in Fig. 2-2 and the contact point c would probably at L/2. Suppose the exact contact time is at t_j(Fig. 2-3), then the clearance due to free expansion and shrinkage hereafter can be estimated by

$$\Delta=L[(T_a+20)\varepsilon_1+(T_b-20)\varepsilon_2]/2 \qquad (2.12)$$

where $\varepsilon_1, \varepsilon_2$ are the corresponding coefficients of heat expansion of material 1 and 2.

C. Computer aided Education

CAE has been widely used at some universities and research centers. A lot of video tapes for self-study are also well spreaded. For teaching system dynamics such as time discrete system, switching theory, nonlinear system, control theory etc. IEEE Transaction of Education recommends the following packages as the major category, these are:

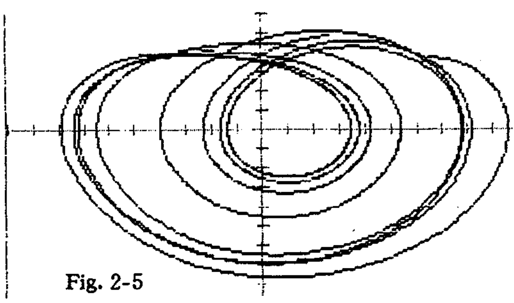
Fig. 2-5

Simon, PC-Matlab, Ms-Kermit, Phaser, Micrologic, Ventura, Volkswriter, Wordperfect, Msword, Microtex ···, This especially benefits engineers to feel and to look at.

An example is the demonstration of chaos phenomena, which is very hard to explain. With the aid of software package "phaser" a phase plot displays all the "strange" characters as shown in Fig. 2-5.

D. Mapping

Mapping here means to transfer the idea from one area to another. This is a general way of "analog" for teaching engineers. e. g. It is well known that telecommunication with lunar satellite is using a special frequency radio signal which can easily pass through the ion zone without too much decay. A similar question is that, Is there the possibility by using a special wave length laser to pass though the liquid media without too much decay? A "mapping" answer may be helpful to evaluate the possibility of using laser. This is: According to the theory of system dynamics, natural modes are the signals for which the loop transmission is unity, hence the answer is theoretically positive.

E. Extended questions

For inducing the creative idea of engineers on system dynamics, extended questions are helpful. For example

* Relation between harmonic balance and least square method.
* Hardware of Vector transformation in real world.
* Check the following transition matrix, is this system linear?

$$F(t)=\begin{bmatrix} \exp(-2t) & 1 \\ 0 & 1-\exp(-t) \end{bmatrix}$$

* What is negative frequency?

many universities have fixed their own problem based package with different level. Practice shows its effectiveness and attractiveness. All questions are as compact as possible but still show the intended points.

F. Advanced technique introduction

System dynamics is well developed in both directions, theory and application. New idea and new system gradually become indispensable technologies in industry, such as expert system, neural networks, variable structure control, fuzzy control, etc. Training program can not cover all these topics but a primary introduction is valuable, It is not only benefitial to engineers but also to directors and decision makers.

G. Summary mode

For engineers it is helpful first to show the global situation of new technologies or ideas, and then the specific theory. In this case teaching material is better composed in summary mode. An example is the introduction of white noise in signal analysis as shown in the following table.

DISTRIBUTION OF WHITE NOISE	FORMULA
NORMAL	N(0,1) : 1
UNIFORM	U(0,1) : U
EXPONENTIAL	−LOG(1−U)
LOGISTIC	LOG(U/(1−U))
CAUCHY	TAN(PI(U−1/2))
EXTREME VALUE	LOG(−LOG(1−U))
LOGNORMAL	EXP(Z)
DOUBLE EXPONENTIAL	LOG(2U), IF U<0.5
	−LOG(2(1−U)), IF U>0.5

Like the design sheet used for engineering this method gives quick reference and a distinct picture.

3. PRACTICE

"All experience is an rich, to build upon" [* 1]. Practice is an intuitive source of knowledge, either for social science or for natural science. It helps both enhancing the understanding of related theory and serving as a criteria of theory. The practice frame work suggested consists of four parts, i. e,

(a) Analog computer practice

This is mainly for continuous system. The whole system can work independently or combine with other real facilities. For example, XY-plot of limit cycle explains why clearance in mechanical connections in harmful? Correlation method in system identification shows how to reduce the noise disturbance in state estimation event.

(b) Digital computer practice

The softwares recommended are as follows,

* Cubic spline and least square;
* Difference and Differential equation;
* System analysis and simulation;
* Optimal control system design;
* Operational Research;
* Signal analysis;
* System Identification.

Others are only used for demonstration in class.

(c) Typical control system manipulation

According to the modified training schedule the following control systems are selected,

* Temperature control system;
* 3-Phase asynchronous motor speed control system;
* CNC system;
* Paper production control system.

Data in operation are gathered, analyzed, and compared with the computed values on the basis of formulated mathematical model.

(d) Plant existing problem solving

This is an important portion for engineers, because they have to treat practical or theoretical problems existed in company or research establishment during study system dynamics. Company will act as a sponsor if some engineering problems can be solved or some methods of treatment are suggested. This reflects the specific tie of training engineers and social requirement. An real example of this work is as follows,

The problem from machine shop is about the undercut effect of milling helix slot, as shown in Fig. 3-1. In order to get accurate surface a modified blade curve is needed. Take XOY as the coordinate, then in C-C section plane the equations of machine part and cutter are as follows,

$$\sin^2\beta \cdot x^2+y^2=\frac{1}{4}D^2 \tag{3.1}$$

where

$$(x-e)^2+(y-f)^2=dc^2 \tag{3.2}$$

$$e=\frac{b}{2}ctg\beta, f=\frac{1}{2}(D+d) \tag{3.3}$$

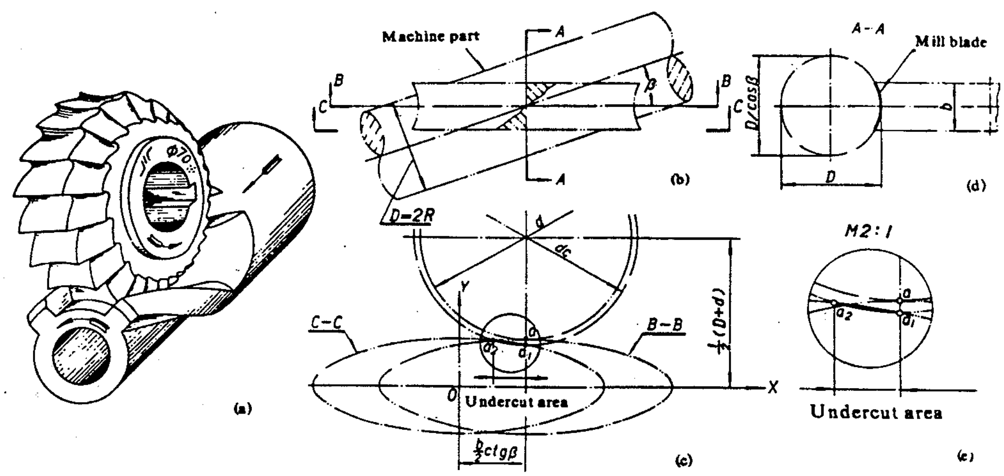

Fig. 3-1

The optimal cutter diameter dc * in different section can be determined by lagrangian function.

$$F(x,y,\lambda)=(x-e)^2+(y-f)^2+\lambda(\sin\beta^2x^2+y^2-\frac{1}{4}D^2) \tag{3.4}$$

—lagrangian multiplier.

Take (x^*, y^*) as the tangent point, then (x^*, y^*) satisfies the following equations.

$$\begin{aligned} \frac{\partial F}{\partial x}&=2(x^*-e)+2\lambda\cdot\sin^2\beta\cdot x^*=0 \\ \frac{\partial F}{\partial y}&=2(y^*-f)+2\lambda\cdot y^*=0 \\ \frac{\partial F}{\partial \lambda}&=\sin^2\beta\cdot(x^*)^2+(y^*)^2-\frac{1}{4}D=0 \end{aligned} \tag{3.5}$$

$$\because \lambda=\frac{f-y^*}{y^*} \qquad \therefore x^*=\frac{ey^*}{y^*\cos^2\beta+f\sin^2\beta}\left(\frac{ey^*}{y^*\cdot\frac{\cos^2\beta}{\sin\beta}+f\cdot\sin\beta}\right)^2+(y^*)^2=\frac{1}{4}D^2 \tag{3.6}$$

$$dc^*=\sqrt{(x^*-e)^2+(y^*-f)^2} \tag{3.7}$$

After succesively evaluating dc^* in different section. An optimal blade curve can be obtained. Practice shows the final accuracy is satisfactory.

4. PERFORMANCE ITEMS

In order to check the training quality, five items have to get through, these are :
(a) Analytical ability
It means the ability of modelling, analysis, simulation, design optimization, and engineering realization. The key point is that problem solving or decision making should be based on the theory and application of system dynamics. One interesting example is the population growth control model in social science.
(b) Computing ability
Training program provides two branches to manipulate digital computers, application program practice and utilization of AD/DA card for information acquisition, system analysis, and control. It would be checked on computer operation.
(c) Physical understanding
It means to explain some events with practical idea on the basis of their experience and concept mastered. It represents their analytical and investigative ability.
(d) Operation skill
This will be done on real operation of laboratory facilities to check their carefulness, correctness and skillfulness.
(e) Creative idea and Orgainzation
In homework and discussion seminar, their creative idea will pour out. This is a very important performance of training.

5. TRAINING DIAGRAM

After ten years training practice a summarized block diagram is formed. It covers all the activities scheduled, including theory teaching and practical operation. It makes a feature of flexibility and efficiency. All training procedures are closely connected and aided by digital computers.
Master of theory, practice of problem, and creation of idea will be the main aim of the whole trining. Figure. 5-1. shows the skeleton diagram of engineer training.

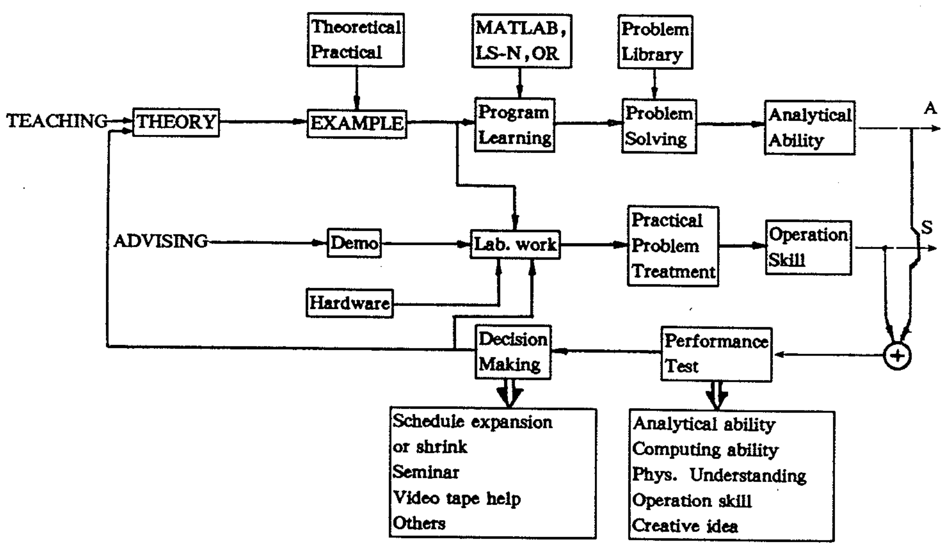

Fig. 5-1

6. CONCLUSION

1. System dynamics covers a lot of areas not only in the sense of technology but also of methodology for decision.
2. For engineers and managers system dynamics is one important factor of their academic potential.
3. Ten years training practice shows the schedule is efficient and attractive. The kernel portion is "Theory, Demonstration, program, and exercise". The main problem is the time duration for training.
4. This schedule (with some changes) also can be used for graduate students.

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