Parameter fitting for anisochronic models by means of moments

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Abstract—Time delay systems are an important category of dynamic systems. Systems with delays, latencies and after effects can be described by using anisochronic models. This paper introduces an original approach to parameter estimation of a linear anisochronic model with the fixed plain structure of the type which is applicable for the control design of processes conventionally described by a serial combination of a rational transfer function and a transportation delay. This anisochronic model contains delays in both input and state. The model is very universal and it can be used for modeling both oscillating and non-oscillating systems. It is described how to convert the conventional linear models of various orders into the linear anisochronic model containing only five parameters. It is also shown how to estimate the parameters of this linear anisochronic model from the step responses. The simple computational formulas for parameter estimation are derived and then used for these purposes. Some of the obtained results are generalized for more complex anisochronic models at the end of the paper. The applicability of the suggested methodology is presented by three examples in the Matlab/Simulink programming environment.

***Keywords*—**Anisochronic model, approximation, average residence time, parameter estimation.

I. INTRODUCTION

TIME delay (dead-time, hereditary) systems are an important category of dynamic systems. We can meet this category of systems in a wide range of application including chemical processes, thermal systems, communication and transportation systems, metallurgical processing systems, power systems, remote control etc., see [9]-[12].

If we want to control a process, we must get to know its properties. Mostly, a model is obtained through system identification and the obtained model is then used for the control design. In most cases, the controllers maintain process variables around operating points; therefore linear dynamical models of plants are predominantly used for control design. The models are usually expressed by a serial combination of rational transfer function and a transfer function of transport delay, as in [1], [6], [7], [18].

Systems with delays, latencies and after effects can be described by these standard models or by anisochronic models.

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In comparison with the standard model, the transfer function of the anisochronic model contains delays in both inputs and states. In the case of a time invariant linear continuous system with lumped delays, the system can be described by differential-difference equations, see e.g. [7]—[11], [15]. These equations separate accumulations and delays as a different kind of dynamics. Parameter estimate of anisochronic models is more difficult than parameter estimate of standard models. Therefore several methods were suggested for this purpose, mostly for anisochronic models with plain structures; see [2], [4], [7], [13], [14].

II. LINEAR ANISOCHRONIC MODEL BASED ON FIVE PARAMETERS

For most practical cases linear anisochronic model (1) is sufficient for description of continuous SISO time delay systems around operating points, see [2], [4], [8], [9]. The transfer function $G_a(s)$ of this model contains only five parameters, see (1),

$$G_a\left(s\right)=\frac{K\cdot e^{-s\tau_u}}{\left(\tau_1\cdot s+1\right)\left(\tau_2\cdot s+e^{-s\cdot\tau_y}\right)}, \tag{1}$$

where K is the process static gain, τ_u is the pure input time delay, τ_1 and τ_2 are the time constants and τ_y is the feedback time delay. The variable s represents the complex argument defined by the Laplace transform. The parameters are depicted in Fig.1, where I represents the position of the inflection point, p is the tangent at the inflection point I, see [3], [4].

In the time domain the model (1) is described by equation (2).

$$\tau_1\tau_2 y''\left(t\right)+\tau_2 y'\left(t\right)+\tau_1 y'\left(t-\tau_y\right)+y\left(t-\tau_y\right)=Ku\left(t-\tau_u\right) \tag{2}$$

In the state–space representation the model (1) can be described by equations (3), (4) and (5).

$$\dot{x}_1\left(t\right)=-\frac{x_2\left(t-\tau_y\right)}{\tau_1\cdot\tau_2}-K\cdot u\left(t-\tau_y\right), \tag{3}$$

$$\dot{x}_2(t) = x_1(t) - \frac{x_2(t)}{\tau_1} - \frac{x_2(t-\tau_y)}{\tau_2}, \tag{4}$$

$$y(t) = -\frac{x_2(t)}{\tau_1 \cdot \tau_2}. \tag{5}$$

The block diagram of model (1) is depicted in Fig. 1.

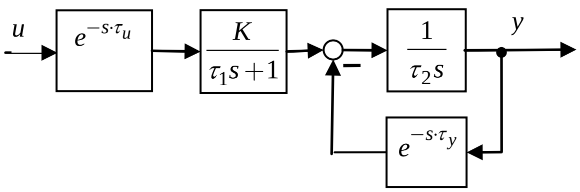

Fig. 1 Block diagram of model (1)

Because the delay τ_y is in the denominator of transfer function (1), then characteristic equation (6) is transcedental in s and has an infinite set of roots [7], [9].

$$(\tau_1 \cdot s + 1)\left(\tau_2 \cdot s + e^{-s\cdot\tau_y}\right) = 0. \tag{6}$$

For this reason, it can be expected to be a better approximation of the dynamics of high-order systems which are conventionally described by a serial linkage of pure transportation delay T_u and a rational transfer function in the form

$$G(s) = \frac{K}{A(s)} \cdot e^{-s\cdot T_u}, \tag{7}$$

where K is the process static gain and $A(s)$ is a polynomial.

Model (1) is stable if $\tau_y/\tau_2<\pi/2$, overdamped if $\tau_y/\tau_2<1/e$, critically damped if $\tau_y/\tau_2=1/e$ and underdamped if $\tau_y/\tau_2>1/e$, where e is Euler's number. Therefore model (1) may be used both for nonoscillatory and oscillatory processes [4], [9].

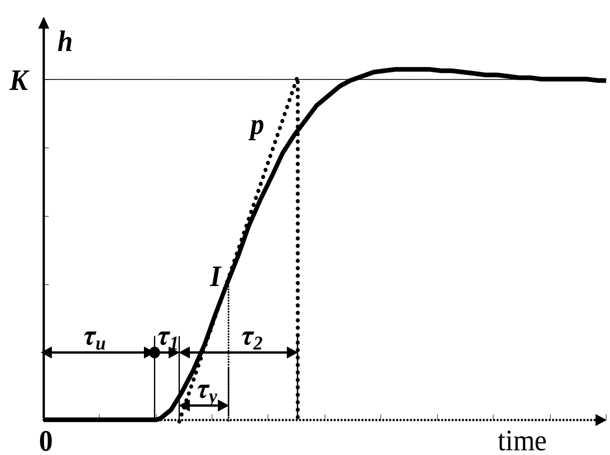

Fig. 2 Unit step response $h(t)$ of model (1)

The parameters K, τ_1, τ_2, τ_u and τ_y can be estimated from the unit step response $h(t)$ by the graphical method, see Fig. 2. But this approach is based on local measurements at a few points. If the signals are corrupted with noise then this graphical construction may lead to large errors. The position of the inflection point I is also vague. To improve the estimates, the method of moments is further applied.

III. METHOD OF MOMENTS

The method of moments [1], [5], [17] is based on the computation of some integral quantities. The two integrals (8), and (9) can be determined for a more reliable estimate of the parameters of anisochronic model (1).

$$M_0 = \int_0^\infty \left(K - h(\tau)\right) d\tau \tag{8}$$

$$M_1 = \int_0^\infty \tau \cdot \left(K - h(\tau)\right) d\tau \tag{9}$$

Integrals (8) and (9) can be determined using the Laplace transform and the theorem of the final value.

$$M_0 = \lim_{t\to\infty} \int_0^t \left(K - h(\tau)\right) d\tau = \lim_{s\to 0}\left(\frac{K}{s} - \frac{G_a(s)}{s}\right)$$
$$= \lim_{s\to 0}\left(\frac{K}{s} - \frac{K.e^{-s\cdot\tau_u}}{s(\tau_1 s+1)\left(\tau_2 s + e^{-s\cdot\tau_y}\right)}\right) = K\cdot\tau_{ar} \tag{10}$$

(10)

$$\tau_{ar} = \tau_1 + \tau_2 - \tau_y + \tau_u = \tau_p - \tau_y \tag{11}$$

where τ_{ar} is the average residence time and τ_p is the transient time of anisochronic model (1), see Fig. 3.

Similarly integral (9) can be determined.

$$M_1 = \lim_{t\to\infty}\int_0^t \tau\left(K - h(\tau)\right) d\tau$$
$$= \lim_{s\to 0}\left(-\frac{d}{ds}\mathcal{L}\left\{K - h(\tau)\right\}\right)$$
$$= \lim_{s\to 0}\left(-\frac{d}{ds}\left(\frac{K}{s} - \frac{G_a(s)}{s}\right)\right)$$
$$= -K\cdot\lim_{s\to 0}\frac{d}{ds}\left(\frac{1}{s} - \frac{e^{-s\tau_u}}{s(\tau_1 s+1)\left(\tau_2 s + e^{-s\tau_y}\right)}\right)$$

$$= K\left(\frac{\tau_{ar}^2+\tau_1^2+\tau_2^2}{2}-\tau_2\cdot\tau_y\right). \tag{12}$$

where $\mathcal{L}$ denotes the Laplace transform.

For anisochronic model (1) with respect to (10) and (11) it holds

$$K\left(\tau_1+\tau_2+\tau_u\right)-M_0 = K\cdot\tau_y\,, \tag{13}$$

which may be used for the determination of parameter τ_y. The area $K\cdot\tau_y$ is depicted in Fig. 3.

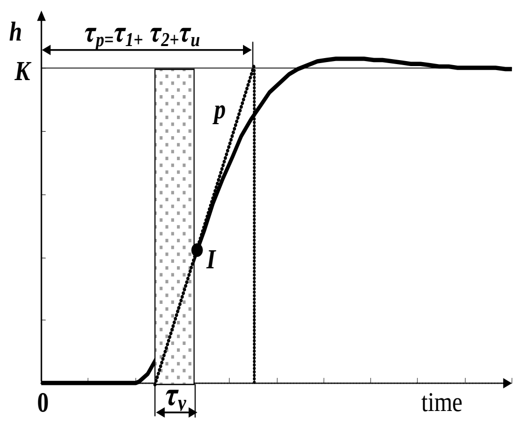

Fig. 3 The marked area $K\cdot\tau_y$

IV. Calculation of Moments

Since digital computers are used for data processing, continuous measurements are converted into digital form. The moments M_0 and M_1 can be obtained from a sampled data record $h(k\cdot\Delta t)$, $k=1,2,...,N$ of the unit step response, where Δt represents the sampling period and N relates to the last sample, when the unit step response achieved the new steady state. The integrals (8) and (9) can be computed by a numerical integration, e.g. a trapezoidal or rectangular integration algorithm.

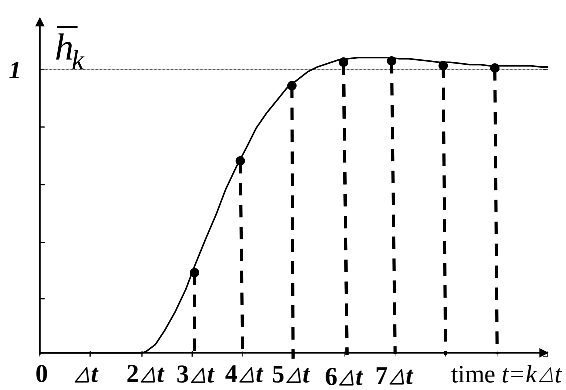

Fig. 4 The normalized step response $\overline{h}_k$

For the calculation we can use the normalized step response $\overline{h}_k$ (see Fig. 4), where

$$\overline{h}_k \triangleq \frac{y_k-y_0}{y_N-y_0}\,. \tag{14}$$

The moments M_0 and M_1 can be then calculated (by means of rectangular approximation) as follows.

$$\begin{aligned} M_l &= \int_0^\infty \tau^l\left(K-h(\tau)\right)d\tau = K\int_0^\infty \tau^l\left(1-\frac{h(\tau)}{K}\right)d\tau \\ &\doteq K\cdot\sum_{k=0}^{N}\left(k\cdot\Delta t\right)^l\left(1-\overline{h}_k\right)\Delta t, \quad l=0,1 \end{aligned} \tag{15}$$

V. Estimation of Parameters

Without the knowledge of the exact position of inflection point I in the step response, one can construct the tangent p and calculate moments (8) and (9) by numerical integration. Then the parameters of anisochronic model (1) can be found in according to the following steps.

1. Determine the static gain K from a graphical construction or through static tests.
2. Determine the time constant τ_2 from a graphical construction, see Fig. 2.
3. Compute the average residence time τ_{ar} from (10)

$$\tau_{ar} = \frac{M_0}{K}\,. \tag{16}$$

4. Determine the transient time τ_p from a graphical construction, see Fig. 3, where

$$\tau_p = \tau_1+\tau_2+\tau_u\,. \tag{17}$$

5. Compute the time constant τ_y

$$\tau_y = \tau_p - \tau_{ar} \tag{18}$$

6. Compute the time constant τ_1 from (12)

$$\tau_1 = \sqrt{2\cdot\frac{M_1}{K}-\left(\tau_{ar}^2+\left(\tau_2-\tau_y\right)^2-\tau_y^2\right)}\,. \tag{19}$$

7. Compute the apparent dead time τ_u

$$\tau_u = \tau_p-\tau_1-\tau_2\,. \tag{20}$$

One will notice that in this method only the time constants τ_p and τ_2 are obtained directly from the graphical construction and they are easily determined by tangent p. The others constants τ_1, τ_u and τ_y are calculated using the values M_0 and M_1. This procedure easily enables the estimation of delays τ_u

and τ_y without knowledge of the exact position of the inflection point *I*.

VI. Two Examples for Estimation of Parameters

Example 1

A system with the transfer function

$$G(s)=\frac{e^{-10s}}{(5s+1)^5} \tag{21}$$

is described by the step response, see Fig. 5. Find parameters of anisochronic model (1) using the presented method.

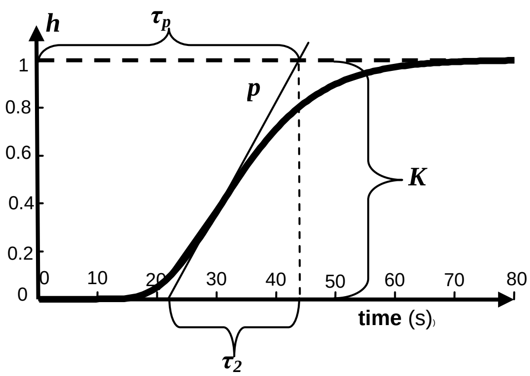

Fig. 5 The unit step response *h(t)* of a system

Solution:

The following parameters are estimated by graphical analysis of the unit step response *h(t)* depicted in Fig. 5: K=1, τ_2=22 s, τ_p=44 s. The values of integrals (8) and (9) are obtained by the numerical integration: M_0=35 s, M_1=675 s^2.

The other estimated parameters obtained by the procedure described in the section V are: τ_1=6 s, τ_y=9 s, τ_u=16 s. The transfer function of anisochronic model (1) is then

$$G_a(s)=\frac{e^{-16s}}{(6s+1)\left(22s+e^{-9s}\right)}. \tag{22}$$

The unit transfer functions of both system (21) and model (22) are in Fig. 6.

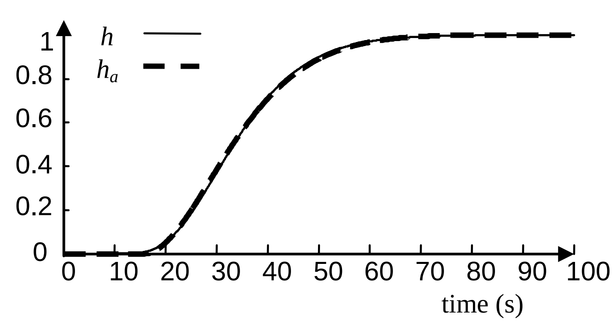

Fig. 6 The unit step response *h* of the system (21) and the unit step response h_a of anisochronic model (22).

Although there is very good conformity between the step response *h* of identified system (21) and the step response h_a of anisochronic model (22), transfer functions (21) and (22) are different. The Bode diagrams of system (21) and model (22) are depicted in Fig. 7. The Bode diagrams display very good conformity for frequencies ω< 1rad·s^{-1} and for higher frequencies $A(\omega)=A_a(\omega)\cong 0$.

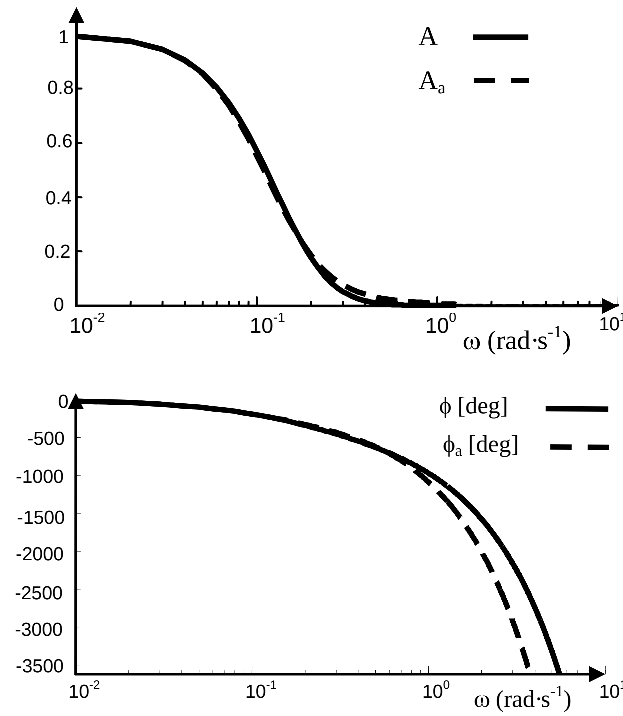

Fig. 7 The Bode diagrams for system (21) and model (22), where $A(\omega)=|G(j\omega)|$, $\phi(\omega)=\angle G(j\omega)$ and $A_a(\omega)=|G_a(\omega)|$, $\phi_a(\omega)=\angle G_a(j\omega)$.

Example 2

A system with the transfer function

$$G(s)=\frac{16e^{-10s}}{s^2+0.8s+16} \tag{23}$$

is described by the step response *h*, see Fig. 8. Find parameters of anisochronic model (1) using the presented method.

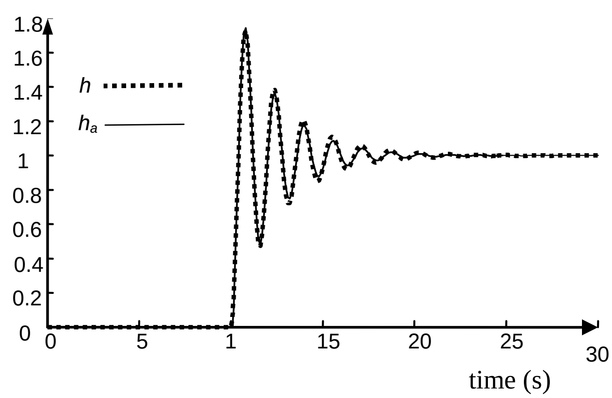

Fig. 8 The unit step response *h* of the system (23) and the unit step response h_a of anisochronic model (24)

Solution:
The procedure is the same as in the example 1. The following parameters are estimated by graphical analysis of the unit step response *h(t)* depicted in Fig. 8: K=1, τ_2=29 s, τ_p=10.4 s. The values of integrals (8) and (9) are obtained by the numerical integration: M_0=10.03 s, M_1=50.42 s^2.

The other estimated parameters obtained by the procedure described in the section V are: τ_1=0.04 s, τ_y=0.37 s, τ_u=10.08 s. The transfer function of anisochronic model (1) is then

$$G_a(s)=\frac{e^{-10.08s}}{(0.04s+1)\left(0.29s+e^{-0.37s}\right)}. \tag{24}$$

VII. Conversion of Transfer Functions

Moments (8) and (9) can also be used for a conversion of a transfer function in the standard form

$$G(s)=K\frac{e^{-T_u s}}{(T_1s+1)(T_2s+1)\cdot\ldots\cdot(T_ns+1)}. \tag{25}$$

to the anisochronic model in form (1).

Moments (8) and (9) can be determined for transfer function (25) and the result is, see [5]

$$M_0=K\cdot T_{ar}, \tag{26}$$

$$M_1=K\left(\frac{T_{ar}^2+T_1^2+T_2^2+\ldots+T_n^2}{2}\right), \tag{27}$$

where the average residence time

$$T_{ar}=T_u+T_1+T_2+\ldots+T_n. \tag{28}$$

It follows from formulas (10) and (26)

$$T_{ar}=\tau_{ar}, \tag{29}$$

and from formulas (12) and (27)

$$\frac{\tau_{ar}^2+\tau_1^2+\tau_2^2}{2}-\tau_2\cdot\tau_y =\frac{T_{ar}^2+T_1^2+T_2^2+\ldots+T_n^2-T_0^2}{2} \tag{30}$$

For example, moments (8) and (9) for transfer function (21) can be calculated using (26) and (27) by the following way

$$M_0=K\cdot T_{ar}=1\cdot(5\cdot5+10)=35\text{ s}, \tag{31}$$

$$M_1=1\cdot\frac{\left(35^2+5\cdot5^2\right)}{2}=675\text{ s}^2. \tag{32}$$

The moments M_0 and M_1 for anisochronic model (22) are approximately the same but they are calculated by derived formulas (10) and (12).

$$M_0=K\cdot\tau_{ar}=1\cdot(6+22-9+16)=35\text{ s} \tag{33}$$

$$M_1=1\cdot\left(\frac{35^2+6^2+22^2}{2}-22\cdot9\right)=674.5\text{ s}^2 \tag{34}$$

VIII. Example for conversion of transfer function

Example 3
Convert the transfer function

$$G(s)=\frac{K\cdot e^{-T_u s}}{(T_1s+1)(T_2s+1)(T_3s+1)}, \tag{35}$$

where K=1, T_1=6 s, T_2=4 s, T_3=2 s, T_u=3 s into the transfer function $G_a(s)$ of anisochronic model (1).

Solution
We can select considering the parameters of transfer function (35)

$$K=1, \tag{36}$$

$$\tau_1=T_1=6\text{ s}, \tag{37}$$

$$\tau_u=T_u=3\text{ s}. \tag{38}$$

The average residence time T_{ar} with respect to transfer function (35) is

$$T_{ar}=T_1+T_2+T_3+T_u=6+4+2+3=15\text{ s}. \tag{39}$$

The average residence time τ_{ar} of anisochronic model (1) is

$$\tau_{ar}=\tau_1+\tau_2-\tau_y+\tau_u=6+\tau_2-\tau_y+3. \tag{40}$$

Because the moment M_0 and the static gain K should be the same for model (35) and model (1) then

$$\tau_{ar}=T_{ar}\Rightarrow\tau_2-\tau_y=6 \tag{41}$$

Similarly the moment M_1 should be the same for both models (35) and (1) therefore

$$M_1=K\left(\frac{T_{ar}^2+T_1^2+T_2^2+T_3^2}{2}\right)=140.5 =K\left(\frac{\tau_{ar}^2+\tau_1^2+\tau_2^2}{2}-\tau_2\tau_y\right)=\left(\frac{15^2+6^2+\tau_2^2}{2}-\tau_2\tau_y\right) \tag{42}$$

It follows from (41) and (42)

$$\tau_2 = 9 \text{ s}, \tag{43}$$

$$\tau_y = 3 \text{ s}. \tag{44}$$

The resulting transfer function of the anisochronic model is

$$G_a(s) = \frac{e^{-3s}}{(6s+1)\left(9s + e^{-3s}\right)}. \tag{45}$$

The unit step response $h(t)$ of model (35) and the unit step response $h_a(t)$ of anisochronic model (45) are depicted in Fig. 9. The Bode diagrams for model (35) and anisochronic model (45) are depicted in Fig. 10.

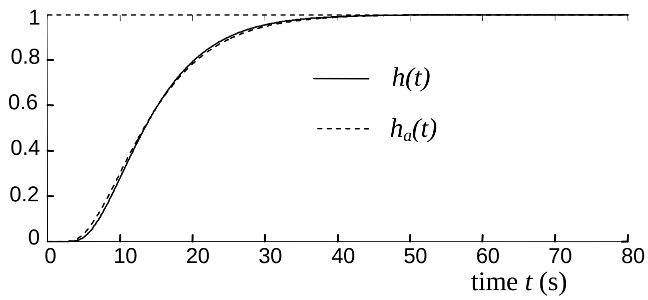

Fig. 9 The unit step response h of model (35) and the unit step response h_a of anisochronic model (45)

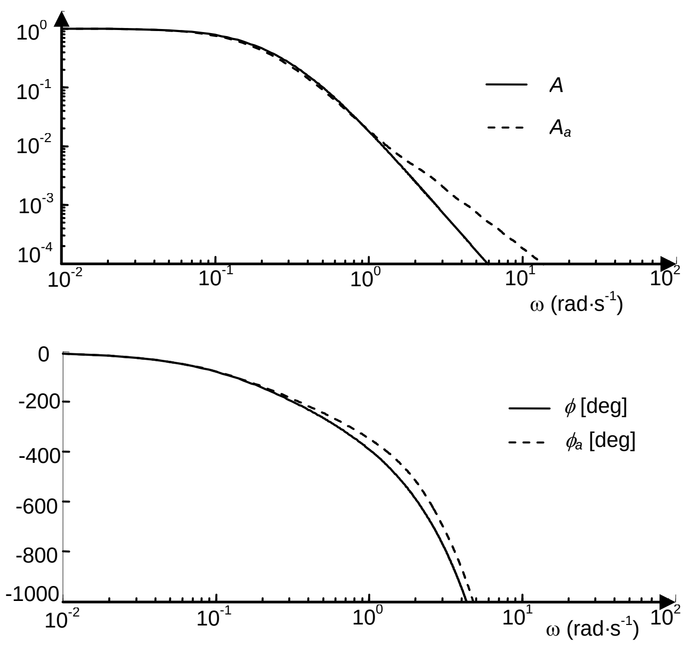

Fig. 10 The Bode diagrams for model (35) and model (45), where $A(\omega)=|G(j\omega)|$, $\phi(\omega)=\angle G(j\omega)$ and $A_a(\omega)=|G_a(\omega)|$, $\phi_a(\omega)=\angle G_a(j\omega)$

IX. Generalization

The transfer function $G_a(s)$ can be factored

$$G_a(s) = {}^1G_a(s) \cdot {}^2G_a(s), \tag{46}$$

where the static gain $K=G_a(0)= {}^1G_a(0)\cdot {}^2G_a(0)$. Then using the MacLaurin series one can obtain

$$\frac{M_0}{K} = \lim_{t\to\infty}\int_0^t \left(1 - \frac{h(\tau)}{K}\right)d\tau = \lim_{s\to 0}\left(\frac{G_a(0)-G_a(s)}{s\cdot G_a(0)}\right)$$

$$= \lim_{s\to 0}\frac{1}{s}\left(-\frac{G_a'(s)}{G_a(0)}s - \frac{G_a''(s)}{G_a(0)}\frac{s^2}{2} - \frac{G_a'''(s)}{G_a(0)}\frac{s^3}{6} - \dots\right)$$

$$= -\frac{G_a'(0)}{G_a(0)} = -\left(\frac{{}^1G_a'(0)}{{}^1G_a(0)} + \frac{{}^2G_a'(0)}{{}^2G_a(0)}\right). \tag{47}$$

Hence with respect to (10)

$$\tau_{ar} = {}^1\tau_{ar} + {}^2\tau_{ar}, \tag{48}$$

where ${}^i\tau_{ar}$ is the average residence time, which relates to the transfer function ${}^iG_a(s)$, i=1, 2.

A system with transfer function

$$G_a(s) = \frac{e^{-s\cdot\tau_u}\cdot\prod_{i=1}^{N_3}\left(T_i\cdot s+1\right)}{\prod_{j=1}^{N_1}\left(\tau_j\cdot s+1\right)\cdot\prod_{k=1}^{N_2}\left({}_a\tau_k\cdot s + e^{-s\cdot {}_y\tau_k}\right)} \tag{49}$$

has, due to (10), (11), (28) and (48), the average residence time

$$\tau_{ar} = \tau_u + \sum_{j=1}^{N_1}\tau_j + \sum_{k=1}^{N_2}\left({}_a\tau_k - {}_y\tau_k\right) - \sum_{i=1}^{N_3}T_i \tag{50}$$

where $N_1, N_2, N_3 \in \mathbb{N}$; $\tau_j, {}_a\tau_k, {}_y\tau_k, T_i, \tau_u \in \mathbb{R}^+$ for $\forall i, j, k$; $\mathbb{N}$ is the set of all natural numbers and $\mathbb{R}^+$ is the set of positive real numbers.

For transfer function (49) the moment M_0 is

$$M_0 = K\cdot\tau_{ar}. \tag{51}$$

X. Conclusion

This paper presents an original approach to parameter estimation of anisochronic model (1) that is suitable for the description of most industrial processes. For this purpose using the moment method, the simple computational formulas were derived for parameter estimation of anisochronic model (1) from a step response or for conversion of a transfer function from form (25) into the transfer function of anisochronic model (1). The practical applicability of this approach is demonstrated by three examples. At the end of the paper is derived the formula for determining the average residence time of the more general anisochronic model.

With respect to the plain model structure, anisochronic model (1) is well suited to be applied in control synthesis based on dynamic inversion. More details about using anisochronic models for Internal Model Control or Smith Predictive Control can be found in [8]-[10], [16], [19], [20].

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