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Structural Identification of Neighborhood Model for Ventilation-Filtration System

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Abstract

In this paper, the problem of structural identification of the neighborhood model for ventilation-filtration system, proposed earlier by the authors, is considered. The refinement of the structure of the model is based on physical considerations and leads to a piecewise trilinear dependencies with a significantly reduced number of coefficients subject to further parametric identification.

Keywords: neighborhood structure, ventilation system, structural identification, parametric identification.

INTRODUCTION

In the article [1] a neighborhood model of the ventilation-filtration system of a production premises was proposed. Here we discuss the problem of structural identification of this model. Any neighborhood model is a system of equations on an oriented graph such that the equations of the model correspond to the vertices of the graph and the entering edges specify the sets of variables participating in the corresponding equation (see details in [2]-[4]). Therefore, any neighborhood model is structurally identified at least at the level of occurrences of variables in the equations. Further, postulating the type of equations (linear, bilinear, etc), we usually deal with parametric identification. Thus we eliminate the difficult problem of structural identification due to the introduction of a large number of parameters, and this is the advantage of the neighborhood-oriented approach. However, for reliable identification of the parameters we need a large number of experimental data and, in addition, we must be prepared for the difficulties created by multicollinearity. For example, the equations of the system proposed in [1], even in the simplest linear case, will contain about one hundred parameters. Therefore, it will be useful to take into account any available information related to the structure of the equations. In fact, for the ventilation-filtration model some simple physical considerations make it possible to significantly reduce the number of parameters. We will consider only the basic part of the model. This part corresponds to the right side of Fig.1 in [1] and describes the ventilation-filtration of the production workshop. Such a restriction is not critical, since the impact of control rooms (left side of Fig.1 in [1]) on energy-saving calculations is small and, on the other hand, the corresponding ventilation-filtration model can be treated similarly.

NEIGHBORHOOD MODEL OF VENTILATION-FILTRATION SYSTEM

The neighborhood structure (see. [2]-[4]) of the ventilation-filtration system of a production workshop in a simplified basic version is shown in the figure below and consists of the following nodes (vertices):

- "Ext" - supply air;
- "Cond" - filtration and thermoregulation (heating or cooling) of supply air;
- "Plant" - production workshop, heat and dust emission;
- "Filt" - extraction and filtration of air before ejection and recirculation.

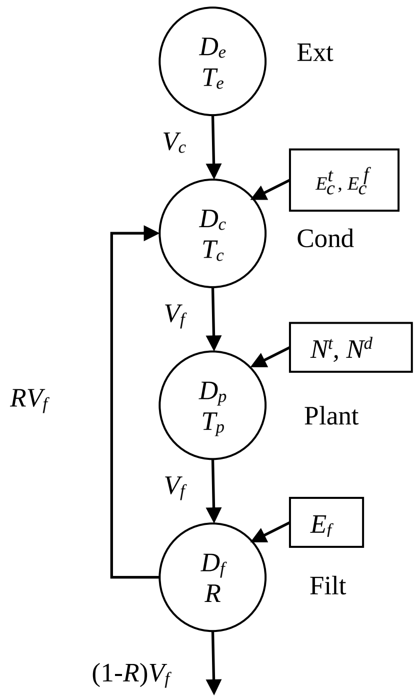

Figure 1: The neighborhood structure of the ventilation-filtration system of a production workshop

In what follows, we will use the mnemonic notation, indexing the variables by letters *e* (for Ext), *c* (for Cond), *p* (for Plant) and *f* (for Filt). The upper *t* and *d* are associated with temperature and dust, the upper *f* is associated with inflow&filtration. In our basic approximation, the system is described by the following variables:

Node "Ext" - D_e, T_e - dust concentration in the supply air and air temperature.

Node "Cond" - V_c, D_c, T_c, E_c^d, E_c^t - volume of supply air per unit time, maximum dust concentration in the air after filtration, air temperature after thermoregulation, energy consumption for inflow&filtration and thermoregulation per unit time.

Node "Plant" - T_p, D_p, N_t, N_d - steady temperature and steady dust concentration in the production workshop, the intensities of heat and dust emission.

Node "Filt" - V_f, D_f, E_f, R - volume of filtered air per unit time, concentration of dust after filtration, energy consumption per unit time for drawing&filtration, coefficient of recirculation.

All values are measured in SI units; $R \in [0,1]$ is the dimensionless coefficient, equal to the ratio of the volume of return air to the entire volume of filtered air.

The separation of variables into states and controls often depends on the problem being solved and often can be changed. Here we will consider the energy consumptions E_c^f, E_c^t, E_f and the recirculation coefficient R as control variables. The variables D_e, T_e, N_t, N_d and N are external, and we will not write the equations for them. The neighborhood model, being formally written, has the form

$$\begin{cases} D_c = F_{cd}\left(D_e, T_e, D_c, T_c, E_c^t, E_c^f, E_f, V_c, V_f, D_f, R\right); \\ T_c = F_{ct}\left(D_e, T_e, D_c, T_c, E_c^t, E_c^f, E_f, V_c, V_f, D_f, R\right); \\ D_p = F_{pd}\left(D_c, T_c, D_p, T_p, V_f, N^t, N^d\right); \\ T_p = F_{pt}\left(D_c, T_c, D_p, T_p, V_f, N^t, N^d\right); \\ D_f = F_f\left(D_p, T_p, V_f, E_f, D_f, R\right). \end{cases} \tag{1}$$

Even in the simplest linear case, these equations contain about fifty parameters. Of course, some evident structural simplifications just lie on the surface. On the other hand, we will see that there are also more subtle observations that make it possible to radically simplify the system (1).

LIMITATION AND BALANCE EQUATION

Internal variables, both state and control, usually should satisfy some technological limitations. In our case

$$\begin{aligned} &T_c \in [T_c^{\min}, T_c^{\max}], T_p \in [T_p^{\min}, T_p^{\max}], \\ &D_c \le D_c^{\max}, D_p \le D_p^{\max}, D_f \le D_f^{\max}, \\ &E_c^f \le E_c^{f\max}, E_c^t \le E_c^{t\max}, E_f \le E_f^{\max}. \end{aligned}$$

Some of these restrictions may depend on external variables. For example, restrictions on temperature and dust concentration may depend on the humidity of the supply air, which we do not consider at this stage. The value of $D_f^{\max}$ is determined by environmental standards and, generally speaking, depends on the weather conditions: air humidity, wind direction and strength, etc. If instead of concentration $D_f^{\max}$ there is a limit $D_V^{\max}$ for the amount of dust emitted per unit time, then $D_f^{\max} = D_V^{\max} / [(1-R)V_f]$. There is also an obvious balance equation for the volumes of supply and exhaust air:

$$V_c + RV_f = V_f \text{ or } V_c = (1-R)V_f \tag{2}$$

In a more detailed model, the balance equation (2) will have the form $V_c = (1-R)V_f + V_{ext}$, where V_{ext} is an additional air leak. The balance equation (2) allows further exclude the variable V_c from the equations.

STRUCTURAL IDENTIFICATION

The first observation that helps simplify the model is that thermoregulation and filtering sub-systems have only two common variables V_f and R. Taking into account also the balance equation (2), we can rewrite (1) as

$$\begin{cases} D_c = F_{cd}\left(D_e, D_c, E_c^f, E_f, V_f, D_f, R\right); \\ T_c = F_{ct}\left(T_e, T_c, E_c^t, V_f, R\right); \\ D_p = F_{pd}\left(D_c, D_p, V_f, N^d\right); \\ T_p = F_{pt}\left(T_c, T_p, V_f, N^t\right); \\ D_f = F_f\left(D_p, V_f, E_f, D_f, R\right). \end{cases} \tag{3}$$

But even in this case the simplest linear model requires about thirty parameters. Now we can write down the three equations for filtration and two equation for thermoregulation using some natural physical consideration related to energy consumption, heat balance and dust balance. We will need the function $S(x) = \max(0, x)$ (Fig. 2):

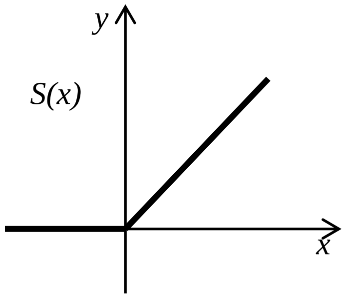

Figure 2: The function $S(x) = \max(0, x)$

Equations for dust filtration

The simplest model for the filtration (inflow + filtration + extraction + filtration) can be described by the following equations:

$$\begin{cases} E_c^f = \beta_c^f V_f + \beta_c^d [V_c S(D_e - D_c) + RV_f S(D_f - D_c)]; \\ D_p = \hat{D}_c + \beta_p^d N^d - \beta_p^f V_f; \\ E_f = \beta_f^d V_f (D_p - D_f) + \beta_f^f V_f. \end{cases} \tag{4}$$

where

$$\hat{D}_c = (1-R)\min\{D_c, D_e\} + R\min\{D_c, D_f\}. \tag{5}$$

Here, for clarity, we do not use the balance equation (2). The first (piecewise trilinear) equation describes the energy consumption in “Cond” for air inflow and filtration of mixed feed and return air. The second (piecewise linear) equation describes the balance for the dust concentration in “Plant”. The third (piecewise bilinear) equation describes the energy consumption in “Filt” for air drawing and filtration. The variable $\hat{D}_c$ means the dust concentration in the mixed feed and return air after filtration to the level $\hat{D}_c$. The equality $\hat{D}_c = D_c$ take place when $D_c \le D_e$ and $D_c \le D_f$, otherwise $\hat{D}_c \le D_c$.

Equations for thermoregulation

The simplest model for the thermoregulation can be described by the following equation

$$\begin{cases} E_c^t = \gamma_c^f \,|(V_c(T_e - T_c) + RV_f(T_p - T_c))|; \\ T_p = T_c + \gamma_p^t N^t - \gamma_p^f V_f. \end{cases} \tag{6}$$

The first (piecewise trilinear) equation describes the energy consumption in “Cond” for thermoregulation of mixed feed and return air. The coefficient γ_c, generally speaking, may depend on heating/cooling mode. The second (linear) equation describes the heat balance in “Plant”. Taking into account the balance equation (2) we can rewrite (4) an (6) as

$$\begin{cases} E_c^f = \beta_c^f V_f + \beta_c^d V_f [(1-R) S(D_e - D_c) + RS(D_f - D_c)]; \\ D_p = \hat{D}_c + \beta_p^d N^d - \beta_p^f V_f; \\ E_f = \beta_f^d V_f (D_p - D_f) + \beta_f^f V_f; \\ E_c^t = \gamma_c^t V_f \,|(1-R)(T_e - T_c) + R(T_p - T_c)|; \\ T_p = T_c + \gamma_p^t N^t - \gamma_p^f V_f. \end{cases} \tag{7}$$

The final system (7) contains only nine coefficients that are subject to further parametric identification (see [5]). Note that intensities N^d and N^t often linearly depend on the intensity of production N and in this case one can replace N^d and N^t in (7) by N.

OPTIMIZATION PROBLEMS AND AN EXAMPLE

The aim of our mathematical model is the optimal control of the ventilation-filtration system, see [1]. This means that the values of all variables must be within the prescribed limits, and energy consumption

$$E = E_c + E_f = E_c^f + E_c^t + E_f. \tag{8}$$

should be minimal. Also, one can consider the minimization problem for the “environmental” functional

$$E^2(k) = (1-k)\left(\frac{E}{E_n}\right)^2 + k\left(\frac{D_f}{D_f^n}\right)^2. \tag{9}$$

where E_n is the nominal value of energy consumption, D_f^n is the nominal intensity of dust emission, and $k \in [0,1]$ is a selectable coefficient. Note that environmental requirements prevail when k→1.

Now consider, as an example, the following case, which is, in particular, relevant for the model of cement production discussed in [1]. Namely, let

$D_e \le D_c \le D_f$, $D_c \le D_p$ and $T_e = T_c$.

These conditions imply the absence of filtration and thermoregulation for the supply air in "Cond". Moreover, here the recirculation does not make sense in connection with the purpose of our optimization, and hence R=0. Then the system (7) can be rewritten as:

$$\begin{cases} E_c^f = \beta_c^f V_f; \\ D_p = \beta_p^d N^d - \beta_p^f V_f; \\ E_f = \beta_f^d V_f (D_p - D_f) + \beta_f^f V_f; \\ E_c^t = 0; \\ T_p = T_c + \gamma_p^t N^t - \gamma_p^f V_f. \end{cases} \tag{10}$$

Thus, for minimization of energy consumption $E(V_f, D_f) = E_c^f + E_f$ we have the linearly constrained two-dimensional quadratic optimization problem:

$$(\beta_c^f + \beta_c^d)((\beta_p^d N^d - \beta_p^f V_f) - D_f) + \beta_f^f) V_f \longrightarrow \min \tag{11}$$

$$\begin{cases} \beta_p^d N^d - \beta_p^f V_f \le D_p^{\max} \\ T_e + \gamma_p^t N^t - \gamma_p^f V_f \le T_p^{\max}; \\ D_f \le D_f^{\max}. \end{cases} \tag{12}$$

CONCLUSION

The general neighborhood model for the ventilation-filtration system of a production workshop, proposed in [1], is reduced to the piecewise-trilinear model with only nine coefficients subject to further parametric identification. In the case of cement production workshop, the described ventilation-filtration model in the simplest case leads to a linearly constrained quadratic optimization problem.

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