Structural and parametric non-stationary modal control systems

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Abstract. The article deals with the aspects of occurring the effect of structural and parametric non-stationary states of various kinds in the models of feeding devices (FD), the latter is considered as the part of a continuous-type mixture-producing aggregate. Relevant features of such an effect are revealed and discussed. In particular, different types of transient modes that occur in the feeding devices under increasing or decreasing the load applied to the intake part of feeders are introduced and described. To demonstrate the complexity of feeding devices models, the distribution of numbers and types of poles for models of different FD-unit configurations have been submitted here. Also we operate with concepts of the so-called autonomously sporadic and forced-modal transient processes, and their images in the forms of 1D-signals and time-frequency distributions are brought in. Finally, the procedures of calculating the modal controller parameters, i.e. the full state feedback matrix, are given in detail.

1. Introduction
When modeling the operating modes of real manufacturing mixture-producing aggregates during multi-ingredient feeding, sporadic changes in the load applied to the intake part of the feeding devices (FD) occur that are caused by feeding into FDs of materials that are initially a priori randomly distributed in the FD-ingredient material containers. As a result, the structural and parametric composition of the control object model can change.

2. The description of structural and parametric non-stationary state
In particular, when the load applied to FD increases, structural adjustment of the feeding process models occurs. For example, when dosing with continuous-type feeding devices (spiral or screw type CTFD [1] – SPFD or SCFD) during load growing (L-rise), a combined transient process (TP) occurs in the form of a flow rate signal at the output of a feeder, including the ordinary TP determined by three poles of the feeding process with a constant feeding frequency, and non-stationary direct time-dependent-frequency TP, in which the nature of the latter is determined by the additional pole creating the exponential form of such a process. Its shape which is well approximated by the impulse response characteristic of the first-order non-periodic process, has been experimentally established (using Cohen’s class time-frequency distributions [2]). Thus, the general order of the forward combined TP model becomes equal to four.

With an opposite change in the load on the CTFD, that is with its decreasing (L-dump), the forward non-stationary combined TP arising in the control object is determined – in addition to the influence of three "native" poles on the process – by three more poles that additionally form the forward non-stationary time-dependent-frequency TP. The latter changes according to the two-exponential dependence of the transient characteristic of the second-order non-periodic type. These factors characterize the concept of a structural non-stationary state.
On the other hand, transient processes occurring in the object, are characterized by a parametric non-stationary state, which is manifested in the current variability of the instantaneous frequency of the flow rate signal during L-rise / L-dump at the input of a feeding device.

### 3. Kinds of transient processes and the distribution of poles in the FD-unit

The same kind of transient processes is formed by the FD-computer modal control system [3, 4] during implementing reverse TPs that restore nominal feeding modes. Such transient processes are referred to as upward reverse TPs (URTP) and downward reverse ones (DRTP). Then the forward non-stationary transient processes, respectively, can reasonably be called the downward and upward forward transient processes (DFTP and UFTP).

Thus, under modal control the effect of forced structural and parametric non-stationary state is created due to a change in the localization of the "poles constellation" of the closed automatic control system.

The degree of modal control complexity that is of the closed system with feedback over the vector of state variables [5], is determined by the number of poles in the constellation.

Table 1 shows the distribution of the poles for models of feeding devices composing the feeding devices unit (FDU).

In accordance with the full structure of the FDU including in total five feeders (two continuous-type feeders – SPFD and SCFD, and three portion feeders – PFDs), provided that the latter model has a squeezing pulse index λ of a dose formation other than 2, a block diagram of the control plant model has been formed.

| FD type | Number of FDs | Number of poles |
|---------|---------------|----------------|
| SPFD    | 2             | - for a single CTFD: 3 (1 pair of conjugated imaginary poles) |
| SCFD    | 1             | 3 (1 pair of conjugated imaginary poles) |
| CTFD    | 3             | - total number of CTFD poles: 9 (3 pairs of conjugate imaginary poles + 3 real poles) |
| PFD, λ=2, N=10 | 2 | 11 (5 pairs of conjugated imaginary poles + 1 real pole) |
| DTFD, λ=2, N=10 | 2 | 22 (10 pairs of conjugated imaginary poles + 2 real poles) |
| PFD, λ ≠ 2, N=10 | 2 | 41 (20 pairs of conjugated imaginary poles + 1 real pole) |
| PFD, λ ≠ 2, N=10 | 2 | - total number of DTFD poles: 82 (40 pairs of conjugated imaginary poles + 2 real poles) |
| FDU (2 SPFDs + 1 SCFD + 2 PFDs), λ ≠ 2, N=10 | 5 | - total number of FDU poles: 91 (43 pairs of conjugate imaginary poles + 5 real poles) |
| FDU, (SPFD + SCFD + 3 PFDs), λ ≠ 2, N=10 | 5 | - total number of FDU poles: 129 (62 pairs of conjugated imaginary poles + 5 real poles) |

### 4. Autonomously sporadic and forced-modal transient processes

Thus, to initiate the modal control process, information is needed on the previous nature of the feeding process that occurs in the conditions of sporadic changes available in the load on the intake part of the feeding device. We call such primary feeding transient processes under varying load conditions...
autonomously sporadic (they include the downward and upward types of forward transient processes, respectively denoted as DFTP and UFTP), and the transient processes that restore nominal dosing modes and are formed by the modal control system, then are called as forced-modal ones (these are the mentioned above URTPs and DRTPs).

The images of autonomously sporadic processes recorded experimentally and displayed in a multidimensional time-frequency format of Cohen’s class wavelet distributions [6, 7], and also reverse processes such as URTPs and DRTPs are presented in figure 1 and figure 2.

When the load on the feeder increases, with the help of the wavelet map (a Cohen’s class distribution) of the disturbed autonomous-sporadic mode, the system evaluates the time constant T (figure 2), and then relevant required values of time constants T1 and T2 of the upward reverse transient process (URTP) are determined – figure 1.

If the load drops, the modal control system estimates the time constants of the forward process of the UFTP type, according to which a certain time constant of the downward process DRTP is set.

These procedures are performed in real time in the framework of the modal control algorithm, and as a result, the modal controller parameters are calculated, with the help of which reverse transient processes such as URTP and DRTP are implemented.

Figure 1. The centered transient process in the spiral feeder in the load reduction mode (chirp-signal); reconstructed by the wavelet matching pursuit algorithm (MP – [2]) feeder flow rate signal, as well as the approximation error of the signal (a); multidimensional chirp-signal image with the increasing time-dependent instantaneous frequency (b).
5. Implementing the algorithm of modal controlling the dosing process

The procedure for implementing the algorithm of modal controlling the dosing process, including the technology of forced localization and relocalization of the closed automatic control system (ACS) poles under conditions of non-stationary processes in the “executive mechanism – FD” system, has been considered on the example of a continuous-type feeder operating in a disturbed mode after a load regime of L-rise type.

It is advisable to apply such a procedure in multidimensional-in-a point systems using the wavelet medium as a means of effective displaying one-dimensional signals. The calculation of the modal controller parameters, that is the determination of the feedback matrix $K$ over the full vector of state variables, is reduced to its calculation by the Ackermann formula [5, 8]:

$$K = [0 \ 0 \ 0 \ 1] \cdot Q_c^{-1} \cdot \alpha (A)$$

where $Q_c^{-1}$ is the inverse controllability matrix: $\alpha (A)$ – the matrix polynomial formed according to the Cayley-Hamilton theorem [5]. To simplify the calculations, the models are taken only for the variable components of the feeding process (the constant components of the process determined by zero poles of feeding process models and non-stationary structural and parametric transient processes are ignored).

![Figure 2](image)

*Figure 2.* The centered transient process in the screw feeder in the load growth mode (chirp-signal); the signal reconstructed by the wavelet matching pursuit algorithm (MP), as well as the approximation error of the signal (a); multidimensional chirp-signal image with the falling time-dependent instantaneous frequency (b).
The parameters of the inverse controllability matrix, that is the state matrix A and control B, are taken from the vector-matrix model that is implemented within the procedures of the algorithm for modal controlling the feeding process:

\[
\begin{bmatrix}
A_1 & A_2 & A_3 & A_4 \\
\vdots & \vdots & \vdots & \vdots \\
A_{41} & A_{42} & A_{43} & A_{44}
\end{bmatrix}; \quad B^T = [B_{11} \mid B_{11} \mid B_{11} \mid B_{11}]^T
\]

\[
\begin{bmatrix}
(AB)_{11} \\
\vdots \\
(AB)_{41}
\end{bmatrix}
\]

\[
AB =
\begin{bmatrix}
(AB)_{11} \\
\vdots \\
(AB)_{41}
\end{bmatrix}
\]

where \( (AB)_{11} = A_{11}B_{11} + \ldots + A_{14}B_{41} \);

\[
\vdots 
\]

\[
(AB)_{41} = A_{41}B_{11} + \ldots + A_{44}B_{41}
\]

\[
A^2B = A(AB) = [(A^2B)_{11}|(A^2B)_{21}|(A^2B)_{31}|(A^2B)_{41}]^T,
\]

where \( (A^2B)_{11} = A_{11}(AB)_{11} + \ldots + A_{14}(AB)_{41} \);

\[
\vdots 
\]

\[
(AB)_{41} = A_{41}(AB)_{11} + \ldots + A_{44}(AB)_{41}
\]

\[
A^3B = A(A^2B) = [(A^3B)_{11}|(A^3B)_{21}|(A^3B)_{31}|(A^3B)_{41}]^T,
\]

where \( (A^3B)_{11} = A_{11}(A^2B)_{11} + \ldots + A_{14}(A^2B)_{41} \);

\[
\vdots 
\]

\[
(A^3B)_{41} = A_{41}(A^2B)_{11} + \ldots + A_{44}(A^2B)_{41}
\]

Thus, the controllability matrix:

\[
Q_c = [B|(AB)_{11}|\ldots|(AB)_{41}|((A^2B)_{11}|\ldots|(A^2B)_{41}|((A^3B)_{11}|\ldots|(A^3B)_{41})]^T,
\]

and the inverse controllability matrix is as follows:

\[
Q_c^{-1} = \text{Adj}[\text{Alg}(Q_c^T)] / \det Q_c
\]

The desired characteristic polynomial is determined by the formula \( \alpha(s) = s^4 - d_1s^3 + d_2s^2 - d_3s + d_4 \), where \( d_1 = (sp_1 + sp_2 + sp_3 + sp_4) \); \( sp_j \) - object poles; \( d_2 = (sp_1sp_2sp_3 + sp_1sp_2sp_4 + sp_1sp_3sp_4 + sp_2sp_3sp_4) \); \( d_3 = (sp_1sp_2sp_3sp_4 + sp_1sp_2 + sp_1sp_3 + sp_2sp_3 + sp_4) \); \( d_4 = sp_1sp_2sp_3sp_4 \).

Consequently, the matrix polynomial has the form \( \alpha(A) = A^4 - d_1A^3 + d_2A^2 - d_3A + d_4I \)

\[
I \text{ – the unity matrix.}
\]

Looking at \( \alpha(A) \), it is easy to see that in the open ACS the poles \( sp_{p2}, sp_{p3}, \) and \( sp_{p4} \) (two imaginary conjugate and the real negative) corresponding to the parameters \( \omega \) and \( T \), affect the transient process type, and just those ones create the frequency component and determine the speed of the transient process.

As a result, we obtain the modal controller matrix \( K \):

\[
K = [0 \quad 0 \quad 0 \quad 1] \quad Q_c^{-1} \quad \alpha(A) = [0 \quad |(T^1)\omega^2 - 1| \quad |(\omega^2 - 1)| \quad |(T^1 - 1)|]
\]

\[
= [K_1 \quad K_2 \quad K_3 \quad K_4].
\]
This matrix is continuously recalculated in real time with an arbitrary step of the millisecond range during the transient process to ensure its time-frequency (chirp-) nature.

Using similar procedures, the computer control system calculates the modal controller parameters for any feeding device or a feeding devices unit.

6. Conclusion
The obtained modal controller parameters make it possible to set the required non-stationary poles of the closed ACS with full state feedback, which are determined by the computer modal control system according to the developed algorithm.

Thus, it was revealed that when modeling the processes in the computer system of modal controlling the feeding regimes, non-stationary structural and parametric transient processes occur, that are caused by secondary reactions to sporadic changes in the input uncontrolled influences (load variation) applied to the intake parts of feeding devices. Models of this kind are the constituent elements of the combined algorithm for modal controlling technological processes of various natures.

Acknowledgements
All comments and suggestions by critical readers and editorial assistance is greatly appreciated.

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