Modern concept of technological processes modal control in a state space combined with wavelet monitoring of current modes

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Abstract. The article deals with the aspects of modal control in spaces of system states and wavelet time-frequency distributions. On the example of a mixture-producing aggregate mathematical models are formed to represent technological feeding material flow rate signals, and the relevant vector-matrix model based on the state space method is developed for the feeding devices unit (FDU). It is revealed that the signals generated by the feeders, are non-stationary in frequency and amplitude. They cannot be adequately interpreted by standard analysis techniques, e.g. such as the Fourier transform. To identify current operating modes of the feeding unit, it is proposed to use the apparatus of wavelet transforms, which allows you to identify local features of the flow signals in a combined time-frequency medium with essentially larger information richness and semantic clarity. For the aim of controlling current modes in FDU a closed automatic modal control system (CACS) with a full state vector feedback has been developed. In the modal control algorithm the feedback matrix is permanently recalculated in real time, which forms the specified localization of the poles constellation. Specified non-stationary feeding modes are demonstrated to represent the essence of modal controlling in the FDU.

1. Introduction

In technological schemes of manufacturing certain products for various purposes related to the production of multicomponent mixtures, the greatest efficiency of the feeding and mixing processes in the preparation of combined products is achieved in continuous-type mixture-producing aggregates. Moreover, regardless of the type of flow sensors, the signals generated by the feeders, are non-stationary in frequency and amplitude. Such signals cannot be adequately interpreted by standard analysis techniques, e.g. such as the Fourier transform.

As a solution to the problem of identifying the current operating modes of the mixing unit, it is proposed to use the apparatus of wavelet transforms, which allows you to identify local features of the flow signals both in time and frequency. As a result of the consideration of modeling methods for the processes of continuous preparation of mixtures, the expediency of studying their dynamics using the state space method, time-frequency wavelet analysis, and also methods to describe the feeding devices unit (FDU) as a controlled dynamic system, is revealed.

2. Modeling the feeding devices unit in a state space

In order to stabilize material flows at a nominal level in the framework of the pre-mixing stage (it’s necessary to obtain high quality mixtures, that is, mixtures with a low degree of heterogeneity), a modal control method for the feeding process is implemented in the work, which implies the creation of conditions for maintaining the required modes due to the directed specific action on the “poles constellation” of a closed feeding system with vector feedback by acting on the executive mechanisms.
of the feeders. In this regard, the problem of the so-called reverse (recovering) transient processes resulting from the forced structural and parametric non-stationary state of the system in case of sporadic uncontrolled changes in input – with respect to a feeding device (FD) – disturbances is solved.

When modeling the FDU in the state space, in order to form a vector-matrix model (VMM) based on the operator functions of the links, a system of differential equations written in Cauchy form and the output equation are compiled. In this case, derivatives of the first and higher orders are written in the form of phase state variables, and a transport delay is approximated by a Padet polynomial-power fraction or by a volume delay in the chain of ten non-periodic links. Presenting the set of variables in the form of vectors, and the collection of parameters in the form of corresponding matrices, we obtain a vector-matrix model of a feeder unit in the state space.

The final model of the feeding flow signals for the spiral and screw feeders of the third order in terms of the state space as a vector-matrix model has the form [1]:

\[
\begin{align*}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= -\omega_2 d_1^2 x_1(t) + X_{d1} \omega_1 u(t) \\
\dot{x}_3(t) &= X_{d0} u(t) \\
u_1(t) &= x_1(t) + x_3(t)
\end{align*}
\]

\[
\begin{align*}
\dot{x}_4(t) &= x_5(t) \\
\dot{x}_5(t) &= -\omega_2 d_2^2 x_4(t) + X_{d2} \omega_2 u(t) \\
\dot{x}_6(t) &= X_{d3} u(t) \\
u_2(t) &= x_4(t) + x_6(t)
\end{align*}
\]

The feeding signal of a discrete feeder is described by a system of differential equations which in the state space will take the form:

\[
\begin{align*}
\dot{x}_7(t) &= \frac{A_0}{2} u(t) \\
\dot{x}_{2l+1}(t) &= x_{2l+1}(t) \\
\dot{x}_{2l+1}(t) &= -((q-1) \omega_b)^2 x_{2l}(t) + u(t) \\
u_b(t) &= x_7(t) + \sum x_{2l}(t), \ i = 4,12
\end{align*}
\]

Here \( I \) – a normalized state variable index; \( q \) is the redefined full harmonic number.

3. Representation of scalar material flow rate signals in a wavelet medium

The requirement to obtain high quality mixtures (with a low coefficient of heterogeneity) implies a uniform (with small fluctuations) supply of the initial ingredients to the mixing apparatus from the feeding devices unit. Therefore, already at the feeding stage, it is necessary to continuously monitor and, accordingly, adjust current operating modes of the feeding devices. Therefore, one-dimensional (scalar) signals of feeding material flows are recorded by means of strain gauge and/or piezoelectric transducers. The obtained primary waveforms of flow rate signals are distorted with noise and non-stationary in frequency, and consequently, at any time they have randomly changing instantaneous dynamic spectra. It is not possible to display such spectra on a visual level by existing traditional methods.

In this regard, a new approach is implemented in the article, which is based on mathematical models and algorithms for approximating, identifying and correcting controlled variables in a certain space. The latter is created on the platform of Gabor wavelet functions [2] and time-frequency wavelet thesauruses formed on their basis. Moreover, the used information about the state of the object is displayed in the wavelet medium in the format of two-dimensional / three-dimensional Cohen’s class quadratic distributions [3]. The Wigner and Choi-Williams distributions were accordingly used as the working and training ones.

The essence of the controlling and monitoring procedure is as follows. When the spectrum structure of the temporal signal vector changes, the time-frequency localization of the corresponding
elements (atoms) on the Wigner map \([2, 3]\) also changes, which should be visualized and registered by the monitoring complex, after which (if necessary) a corrective action is put to the feeding electric drive.

Considering that in the controlled plant individual feeders sporadically (randomly, from time to time) change their output signals (due to variation in input actions arising owing to spontaneous changes in the physical and mechanical characteristics of the ingredients entering the controlled plant), it seems appropriate to observe the general output signal of the controlled plant flow, the wavelet-card of which captures all the signals of individual feeding devices. At the same time, on the operator monitor “nominal” frames (specific window frames – see figure 1) are formed, onto which time-frequency atoms of a wavelet distribution (for example, Wigner distribution) that correspond to the nominal feeding mode, are projected. For continuous-type feeding devices (CTFDs) of spiral and screw type, such distributions with permanent frequencies are thin in frequency (along the ordinate axis) and elongated in time (along the abscissa axis) time-frequency atoms (TFA) on a Wigner map. Therefore, under real operating conditions of feeders, on the wavelet map (W-map), a deviation of a certain TFA (for a CTFD) or a group of atoms (for a discrete-type feeding device – DTFD) sporadically takes place beyond the boundaries of the frame / frames. In this case, the computer control system records the sequence of violation of the rated modes of certain FDs. And as to similar modes, the processing time of the corresponding FD W-map should be less than the time interval between the occurrence of two adjacent-in-time deviations of the TFA outside the frames of two any different FDs or the same feeder.

When fixing the unacceptable deviation of the TFA beyond the borders of the frames, the modal control technology begins to operate.

Feeding processes are controlled by the computer system in a wavelet medium based on a modal control algorithm. The purpose of the algorithm is to stabilize the feeding process at the pre-mixing stage at a nominal level with fluctuations in the output flows owing to sporadic stepwise or exponential changes in the input actions on the feeders.

The essence of designing a modal control system is the synthesis of a closed automatic control system (CACS) with a full state vector feedback by certain placing the poles of this system, followed by determining the feedback matrix (the modal controller parameters), which forms the specified localization of the poles constellation. The synthesis by placing the poles is based on the use of the system model in the state space.

![Figure 1. Waveforms and their time-frequency maps corresponding to a) nominal and b) current (indignant) operating mode for a discrete-type feeder.](image-url)
In real manufacturing feeding systems, the hopper containers of each FD are filled with the materials of the initial ingredients, which have different physical and mechanical properties in each tank (for example, moisture characteristics and/or uniformity degree of particles in composition), therefore during feeding there occurs sporadic variation of the effect of the fed ingredient material on the input part (i.e. material intake part) of the relevant feeder active organ. As a result of this, the frequency of the feeding signal (associated with the rotational speed of the FD executive mechanism—FDEM) changes in transient modes, which ultimately leads the feeding process to a new steady-state frequency mode that does not correspond to the nominal one required at the pre-mixing stage.

Upon receipt of a more uniform and dry (less humidified) substance, the FDEM accelerates due to load shedding on the feeder working body, while the frequency of the material flow signal increases until it stabilizes at a new steady level with a new, non-nominal, performance. But with an increase in the load on the working body of the feeding device the picture is opposite. In both cases, it is required to act on the CACS with modal control in order to stabilize the material flow at a nominal level. But since the action at the intake part and the reaction at the output of the FD have already stabilized at a new level, it is necessary to bring influence to bear upon the internal structure of the CACS in such a way as to change the structural and parametric properties of the system. Thus, it is required to create the effect of a forced structural and parametric non-stationary state by changing the localization of the CACS “poles constellation”.

Consequently, during FDEM-speeding up (that is, when the signal frequency increases due to a decrease in the load (L-dump) on the FD working body), it is necessary—in order to stabilize the flow rate at the nominal level—to reduce accordingly the value of the imaginary conjugate poles pair (for CTFD). As for the reverse transient feeding process in DTFD, the imaginary poles should be reduced only for the most powerful sub-harmonics of the first harmonic in the Fourier model. In this case, the model has the form as follows: $B_1 \sin \omega_1 t + A_1 \cos \omega_1 t$. High harmonics are rejected using low-pass filtering or a high-frequency rejecting filter.

4. Transient processes under L-rise / L-dump

When implementing an upward reverse transient process after L-rise (URTP) is carried out in the frames of modal control, restoration of the nominal feeding mode is performed according to the two-exponential function of the form

$$x(t) = x(t)_{b}e^{i\varphi} + x(t)_{nb}e^{i\varphi} \sin[2\pi f_{var}(t - \tau) - \varphi_0],$$

where $f_{var} = f_b[\{1(t - \tau_b)\} + (f_e - f_b) \{1(t - \tau_e)\} - \exp[(-t - \tau_b) / T_3] T_3 / (T_3 - T_4) + \exp[(-t - \tau_e) / T_4] T_4 / (T_3 - T_4)] - \text{the instantaneous frequency of the chirp-signal (a signal with a time-dependent frequency) of the upward reverse transient process;}

$$x(t)_{nb} = x_{nb} + \left(1 / T\right) t, \quad \tau_b \leq t \leq \tau_e - \text{changing in the amplitude of the variable component of the URTP;}

$$x(t)_{0b} = x_{0b} \{1(t - \tau_b)\} + (x_{0ei} - x_{0bi}) \{1(t - \tau_e)\} - \exp[(-t - \tau_b) / T_3] T_3 / (T_3 - T_4) + \exp[(-t - \tau_e) / T_4] T_4 / (T_3 - T_4) - \text{the non-periodic component of the upward reverse TP.}

Thus, a complete transient graph function for two cycles of load variation (L-rise and L-dump), including a downward forward (DFTP) / upward reverse (URTP) transient processes, as well as an upward forward (UFTP) and a downward reverse (DRTP) transient processes, has the form (figure 2); here the ordinate axis is the flow rate one $x(t)$. Figure 3 shows separately the graph functions of the upward and downward reverse TPs.

The procedure to implement the modal control algorithm for the feeding process including the technology of forced localization and relocalization of open ACS poles under the conditions of non-stationary processes in the “FDEM-FD” system, is considered on the example of a continuous-type feeder in a disturbed mode during load shedding (during a transient process like DRTP).
Figure 2. Cycles of modal controlling the feeding process under L-rise and L-dump.

Figure 3. Waveforms of modal controlling the feeding process after the L-rise (on the left – URTP) and after the L-dump (on the right – DRTP).

5. The procedure of calculating the modal controller parameters

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 [4]:

$$K = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \cdot Q_c^{-1} \cdot \alpha(A),$$

where $Q_c^{-1}$ – inverse controllability matrix: $\alpha(A)$ is the matrix polynomial formed according to the Cayley–Hamilton theorem [5, 6].

This matrix is continuously recalculated in real time with a time step of 10 ms 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 unit.

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

6. Conclusion

Thus, the computer modal system developed for controlling the feeding process performs the functions of stabilizing nominal operating modes of the feeding devices unit at the pre-mixing stage, which contributes to the production of high quality mixtures.
Moreover, it should be noted that all necessary procedures associated with the formation of vector-matrix models of the control plant, the assessment of its controllability, and, if necessary, observability, the operations of converting 1D-signals into multidimensional wavelet distributions, as well as operations to implement the matrix algebra used in calculating the parameters of the modal controller, when testing them in real time, it was shown that the required CPU clock frequency of a computer as part of the computer modal control system does not exceed 500 MHz.

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