A dynamic model of pressure screens for fault detection

Leoncio W. Estévez-Reyes and Guy A. Dumont

ABSTRACT: The "classical" control scheme for pulp pressure screens regards the screen as a static system. Out of several faults that could occur during screen operation, it addresses only the possibility of plate plugging. Among other drawbacks, this method restricts the screen throughput. After testing different parametric and nonparametric methods for fault detection on screens, it was found that a mathematical model developed at the Pulp and Paper Centre in The University of British Columbia has potential for its use as a diagnosis tool. By monitoring some of the process parameters of the screen included in this dynamic model, incipient malfunctions of the screen could be detected and failure could be prevented. The pressure screen model is part of a general strategy for diagnosing and controlling pressure screens.

KEYWORDS: Defect detectors, detection, mathematical models, pressure screens, process control.

Fine screening systems are found in all mechanical pulp plants. The purpose of these systems is to remove certain unwanted constituents from a pulp slurry so that the suspension becomes more suitable for the product in which it will be used: paper, cardboard, etc., *(1)*. Usually, pressure screens are placed after or between refining stages, but this is not the only location for them. In all cases, the principles of operation and control are the same.

There are many configurations of pressure screens in use today, but most of them are built with a cylindrical screen plate. In a typical model, such as the one seen in **Fig. 1**, the incoming stock is tangentially fed into the inside of the cylinder. The pressure will force the passage of the suspension through the openings in the plate to an accept compartment, from where it is tangentially discharged into the accept piping. The rejected material passes down the inner surface of the plate into a reject section, from whence it is discharged into the reject piping. Dilution water, which may or may not be used, can be added into the reject compartment and also into the screening zone. An electric motor, which drives the rotor, is utilized as a means of preventing the screen from plugging and to accelerate the pulp suspension.

Many variables affect the performance of any given pressure screen: plate design, rotor and housing design, flow rates, pressures, characteristics of the pulp, etc. Some of them cannot be modified during operation. Some others can and are of particular interest for screen control purposes.

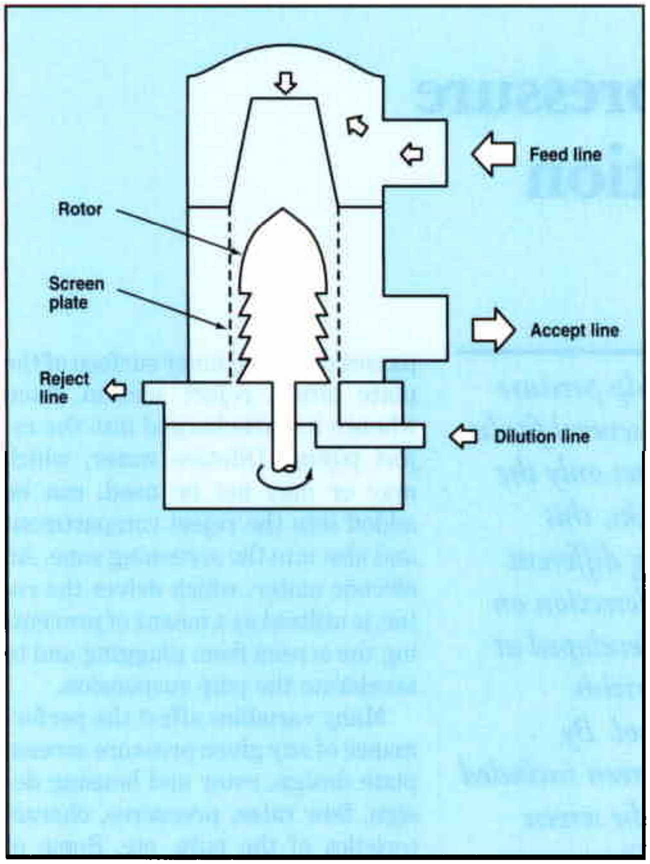
The ideal screen control would allow for the extraction of all the debris in the feedstock without the removal of any acceptable pulp *(2)*. This objective cannot be directly achieved, among other reasons, because there are no reliable on-line measurements of pulp quality in industry. Therefore, the best possible control is one which would optimize the ratio of good fibers/debris, the screen capacity, and the economic and operational aspects of the pulp plants by indirect means.

Screen faults

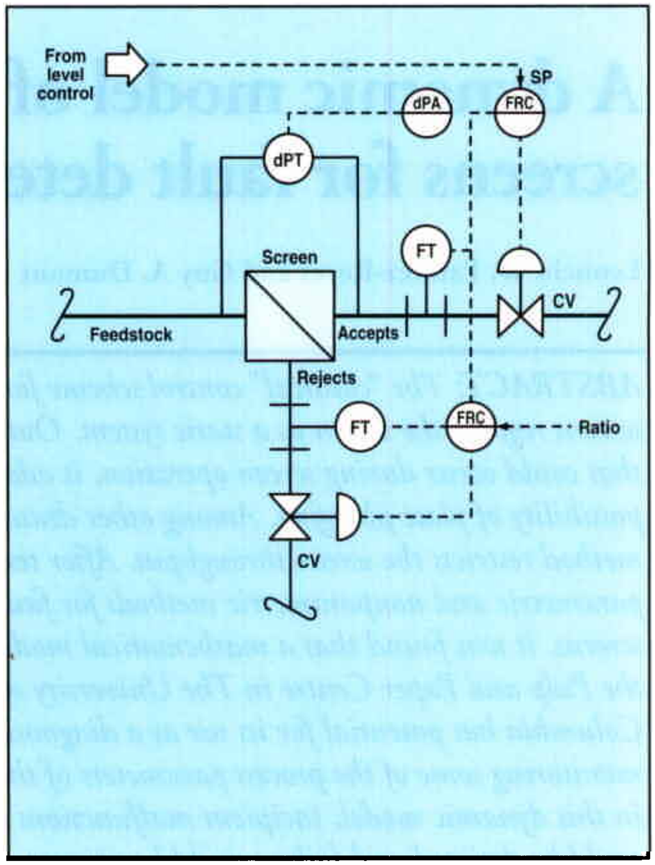
If we use the term *fault* to characterize "the departure from an acceptable range of an observed variable or calculated parameter associated with the equipment" *(3)*, all

Estévez-Reyes and Dumont are, respectively, student and professor at the Dept. of Electrical Engineering and Pulp and Paper Centre, University of British Columbia, 2385 East Mall, Vancouver, BC V6T 1Z4, Canada.

1. Typical pressure screen



2. "Classical" control scheme for screens



pressure screen faults can be grouped in five categories:

1. Blinding. Fibers accumulate within or adjacent to screen plate apertures (or even in the reject piping). Low screen capacity will result from this condition and, in extreme cases, it will lead to plugging and stoppage of the accept pulp flow.
2. High loss of good fibers into the rejects. Either by improper feed consistency, volume of dilution water, or plate perforation.
3. Loss of accept quality. The presence of an undesired percentage of contaminants in the treated pulp would result as a consequence of high rotor speeds, low consistencies, or wrong reject rate.
4. Motor overloads.
5. Flow instability. Due to high flow velocities/cavitation.

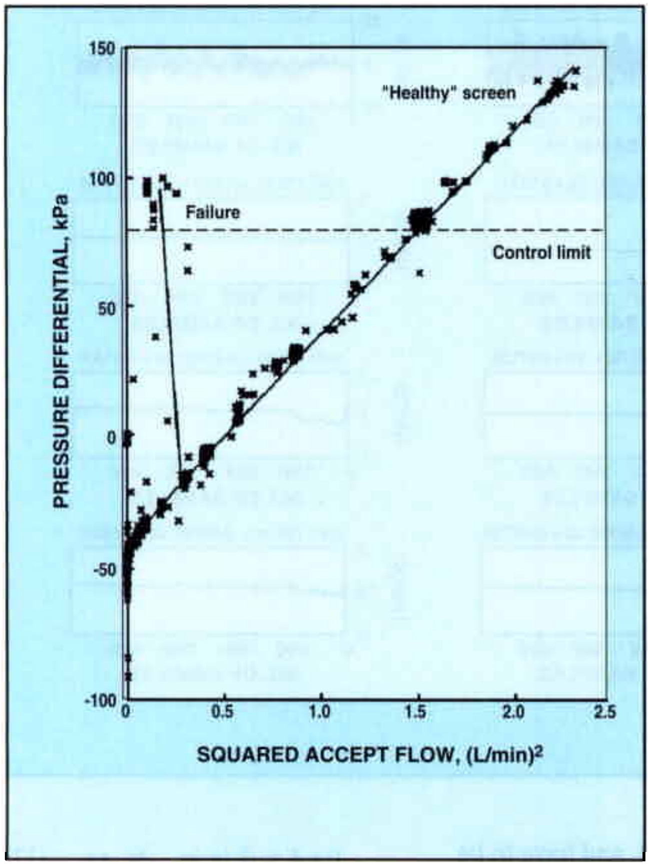
As 2 and 3 are related to pulp quality and, hence, out of the "on-line domain," an automatic fault detection strategy for screens will concentrate on recognizing the remaining faults.

Screen control and FDI

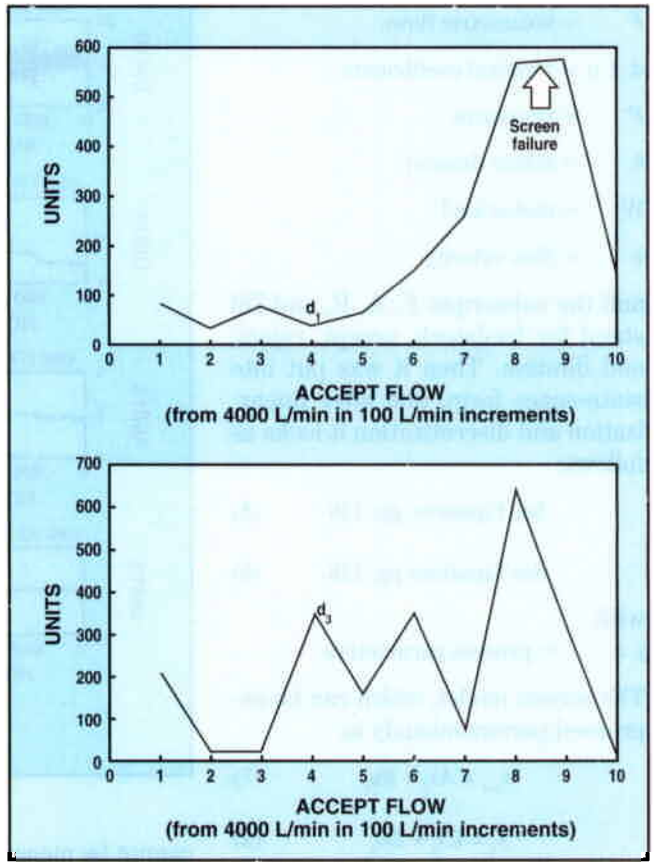
The "classical" control strategy for pressure screens calls for either or both of two requirements to be met: a stable operating pressure and a stable stock throughput measured as a flow rate *(4)*. A standard application of this strategy can be seen in **Fig. 2**. There, the pressure drop across the screen is maintained constant. The accept valve is used to control the screen throughput and the differential pressure is controlled through the ratio of flows: accept vs. reject. However, if the pressure drop increases above a preset level, presumably because of screen plugging, the accept valve will be closed and the reject valve will be fully opened to purge the screen. Usually, an alarm is provided to warn the operator in the event of plugging *(5–7)*. Although some alternatives can be found in the literature, they are variations of this "classical" strategy *(8, 9)*. Besides the alarm described above, no means are provided for the acknowledgment of any possible faults.

It is evident that the "classical" approach used in the pulp mills is not a true fault detection and isolation (FDI) scheme, as it neither recognizes faults nor prevents screens from failing. It merely warns about probable occurrence of failure. That is, the operator can react only after suspected plugging is present with

3. Pressure differential vs squared accept flow relationship for screen. "Healthy" and "blinded" behaviors are caused by differences in pulp consistency.



4. Magnitude of physical coefficients in screen model



all the unwanted consequences that this condition produces: process interruptions, deviation from safe operating conditions, economic losses, etc.

In order to avoid the recurrence of failure, screens are operated at process conditions which are rather conservative, but this practice is not satisfactory. By operating a screen under too cautious differential pressure constraints, its throughput is reduced, its efficiency is affected, and the screen is flushed even when no fault is present. This fact, first pointed out by Gooding and Craig *(10)* and confirmed during the course of this research, is demonstrated by **Fig. 3.**

It should be apparent by now that the common method of dealing with screen faults in industry has fundamental weaknesses. The question is, of the existing approaches in the literature, which one is the best possible alternative to implement as a screen FDI system?

A mathematical model for the screen

In order to choose a true FDI system for the screens, several options were considered for testing, ranging from the simple to the complex. Out of all possible indexes and process variables which do not require a mathematical model of the screen, the list was narrowed down to two alternatives which seemed the most promising. First, the screen motor load was evaluated using statistical control principles. Later, the relationship between the differential screen pressure and the accept flow was explored. In the end, although some improvements were made over the "classical" approach, none of these attempts could be deemed as a true FDI method, as all of them simply warned of a failure after one had occurred. This result suggested the need for developing a mathematical model of the screen, as a more refined and effective fault identification tool.

The dynamic model was derived from first principles: mass balance.

$$0 = F_F - F_A - F_R + F_{Dil} \quad (1)$$

energy balance,

$$0 = g_1F_F + g_2P_F + g_3F_{Dil} + g_4P_{Dil} - g_5F_A - g_6P_A - g_7F_R - g_8P_R + f_1W_3 + f_3k_A + f_3k_R \quad (2)$$

and a dynamic version of Darcy-Weisbach's equation to account for the energy losses inside the screen.

$$\dot{k}_A = d_1k_A + d_2v^2_A \quad (3)$$

$$\dot{k}_R = d_3 k_R + d_4 v_R^2 \quad (4)$$

with

F = volumetric flows

d, f, g = physical coefficients

P = pressures

k = states (losses)

W_s = motor load

v = flow velocity

and the subscripts F, A, R, and Dil stand for feedstock, accept, reject, and dilution. Then it was put into state-space form, and after linearization and discretization it looks as follows:

See Equations pg. 128 (5)

See Equations pg. 128 (6)

with

j, h = process parameters.

The screen model, which can be expressed parsimoniously as

$$x_{k+1} = Ax_k + Bu_k \quad (7)$$

$$y_k = Cx_k + Du_k \quad (8)$$

or, equivalently, using the shift operator D where $Dx_k = x_{k+1}$ and the identity matrix I, as

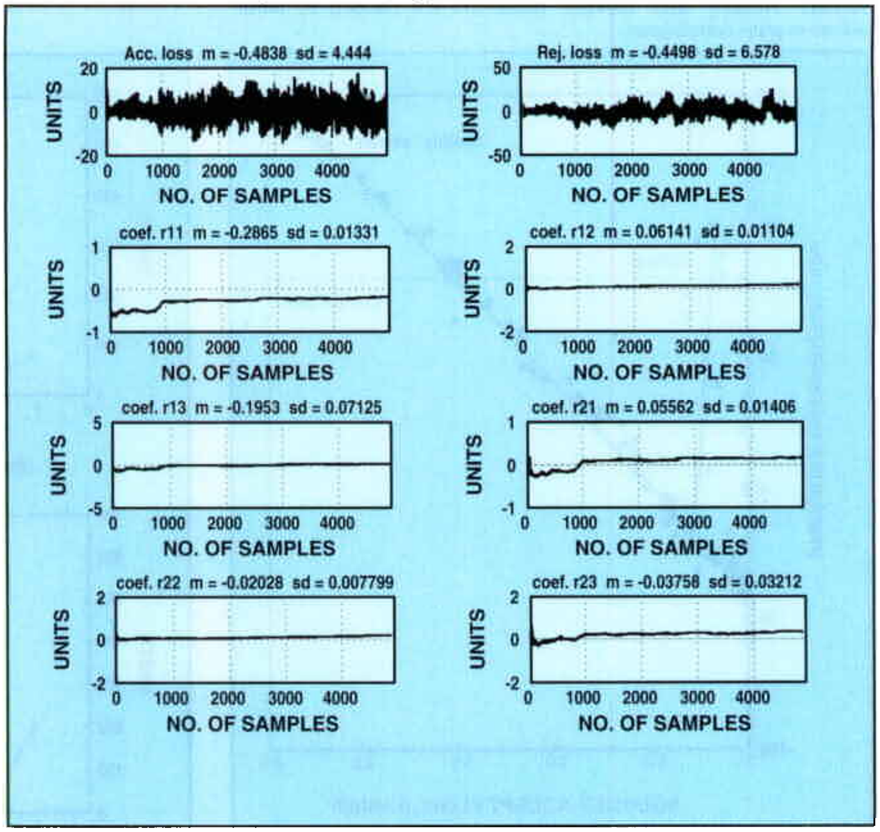
See Equations pg. 128 (9)

is controllable, provided the parameter $j_4 \neq 0$ (which seems true in all cases), and *observable*, provided $j_1 \neq j_2$ (which is also true in the majority of cases), and that makes it ideal for identification.

Model-based FDI

The procedure for detection of faults in the screens involves identifying and monitoring the j_i process parameters that appear in the dynamic model. These four parameters indirectly reflect the physical coefficients of the screen (d_i), and using them to calculate d_1, d_2, d_3, and d_4 should help determine the presence of faults. If the values of the d's stray beyond their normal range, a fault is deemed present. The losses inside the screen

5. Parameters estimated by Kalman filtering



cannot be measured, and have to be estimated simultaneously with the process parameters of the system. For this purpose, an algorithm based on a canonical singular pencil model was implemented.

The main idea behind the algorithm is to rearrange and separate the measurable variables from the process unknowns (in this case, the states and the process parameters in the model), through similarity transformations *(11)*. Accordingly, the model is brought to the representation

See Equations pg. 128 (10)

using the similarity transformations $T_iAT_i^{-1}$, CT_i^{-1} and T_iB, until the submatrices E_*, E_0, A_*, A_0, B_* and B_0 make $P(z)$ a canonical representation. C_* is the noise matrix. From that canonical representation, the pencil can be reordered as

$$x_{k+1} = E_* x_k + \tilde{G}_*(w_k) r_k + C_* e_k \quad (11)$$

$$0 = E_0 x_k \tilde{G}_0(w_k) r_k - J w_k + e_k \quad (12)$$

with

$$\tilde{G}_*(w_k) r_k = [\,-A_* | B_*]\, w_k \quad (13)$$

$$\tilde{G}_0(w_k) r_k = [\,-A_0 | B_0]\, w_k + J w_k \quad (14)$$

That equation can be further refined into

$$s_{k+1} = F_k s_k + D_* e_k \quad (15)$$

$$y_k = H_k s_k + e_k \quad (16)$$

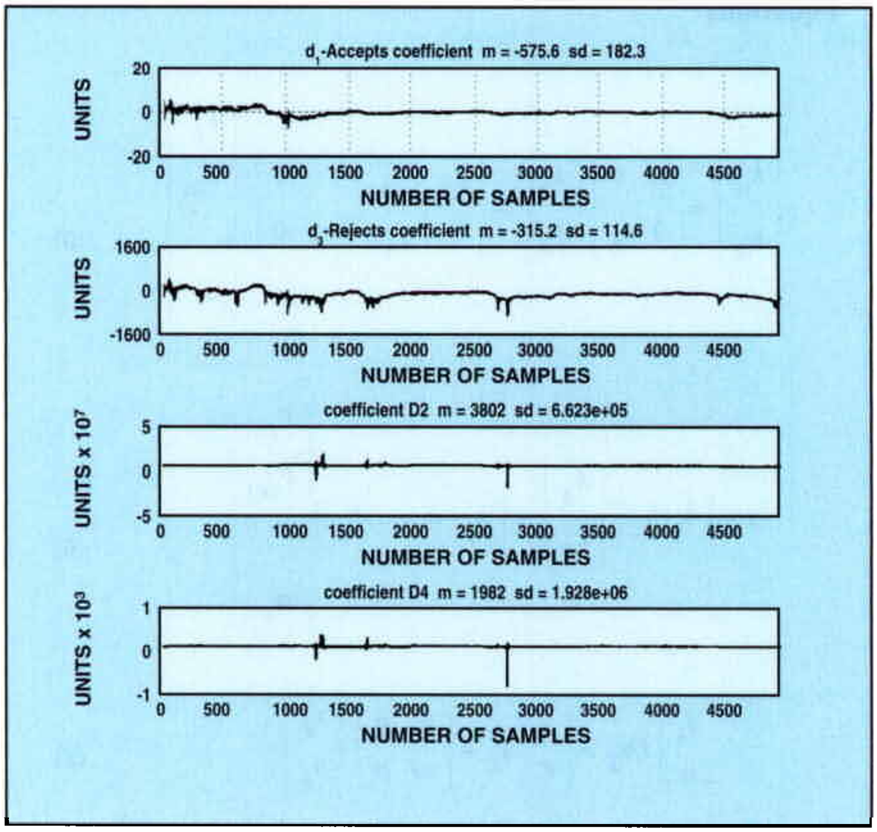
with

$$s_k = \left[x_k^T, r_k^T \right]^T \quad (17)$$

$$H_k = \left[E_0 \tilde{G}_0(w_k) \right] \quad (18)$$

$$F_k = \begin{bmatrix} E_* & \tilde{G}_*(w_k) \\ 0 & I_l \end{bmatrix} \quad (19)$$

6. Screen raw physical coefficients



$$D_* = \begin{bmatrix} C_* \\ 0lxn \end{bmatrix} \qquad (20)$$

Now it is possible to use a Kalman filter to obtain the optimal linear estimate of the augmented vector state s_k, which includes all the unknown states and process parameters of the system, provided that the model for the noise is known. Hence, using a singular pencil model, a nonlinear estimation problem has been reduced to a linear one.

Some results

The model and the identification algorithm were tested in the Pulp and Paper Research Institute of Canada's pulp screening pilot plant. This plant, which comprises three storage tanks, a centrifugal pump, two industrial-scale pulp screens, and the instrumentation required to measure and control all important process variables of the equipment operation, allows for circulation of pulp flows up to 10,000 L/min with a consistency of up to 5%.

In each trial, the feed pressure was kept constant at 350 kPa, the reject flow was fixed at a pre-established rate, ranging from 500 L/min up to 2000 L/min, and the accept flow through the screen was increased in equal steps until the screen was brought to failure. The process variables were constantly monitored and data on pressures, flow rates, temperature, and screen motor load was gathered for off-line analysis. After using the singular pencil identification method presented above, the *d*, physical coefficients of the screen were derived.

As the results in **Fig. 4** show, while the accept flow is less than 4500 L/min, the accept physical coefficient remains below 100 units. When the flow exceeds 4500 L/min the coefficient value starts to grow very fast, suggesting that the passage of fibers is becoming more difficult, presumably because blinding has appeared. The coefficient reaches its maximum shortly after it is confirmed that the screen plate openings are plugged. It is clear then that, by monitoring the averaged coefficients imbedded in our model, failure of the screen could be predicted before it happens. **Figures 5–6** show plots from the various steps in the algorithm: parameters estimated by the Kalman filter and calculated raw coefficients.

During the different trials some interesting observations were made:

1. For accurate results, fast uniform sampling and antialiasing filtering are required. Although most commercial distributed control systems (DCS) do not seem capable of meeting these requirements, a dedicated PC can easily handle them.
2. High noise spikes in the process data can derail the estimation; therefore, they must be filtered out.
3. The choice of parameters in the noise matrix can alter the estimation results. As such, good care must be taken to ensure that the chosen noise model fits the process reasonably well.

Conclusions

The main conclusion of this research is that, in general, the proposed model for the pressure screen seems promising as a true fault detection tool suitable for industrial use. It can give a better idea of the changes in energy losses inside the screen, and those changes can be associated with the different operational faults that might occur to this device. For instance, by monitoring the different physical coefficients imbedded in the model, the occurrence of plate plugging or reject line plugging could be predicted before it happens. A practical implication of this conclusion is that, by implementing such a scheme in a mill, pressure screen systems could be used more efficiently and a more flexible control strategy for them could be put in place, allowing for varying throughput, or handling of higher consistency pulp.

The second conclusion is that the singular pencil matrix has proven to be a suitable simultaneous identification method for parameters and states. It shows good behavior regarding convergence and numerical stability, problems which are associated with the approaches based on use of the extended Kalman filter. It also shows a very important feature: the capability of handling extra equations by simply increasing the size of the matrix. The practical implication here is that, if new relations concerning pulp quality are included in the screen model, the scheme remains unaltered except for the size of the matrices in use.

The corollary is that, as all sophisticated mathematical tools, the benefits of the singular pencil of matrices technique do not come free. A reasonably good *a priori* model of the process noise is required for achieving consistent results. At the present time, two approaches for obtaining such a model automatically are being investigated.

Equations

$$\begin{bmatrix} \dot{k}_A \\ \dot{k}_R \end{bmatrix} = \begin{bmatrix} j_1 & 0 \\ 0 & j_2 \end{bmatrix} \begin{bmatrix} k_A \\ k_R \end{bmatrix} + \begin{bmatrix} j_3 & -j_3 & \dots & 0 \\ 0 & j_4 & \dots & 0 \end{bmatrix} \begin{bmatrix} F_F \\ F_{Dil} \\ \cdot \\ \cdot \\ \cdot \\ w_s \end{bmatrix} \tag{5}$$

$$y = \begin{bmatrix} h_8 & h_8 \end{bmatrix} \begin{bmatrix} k_A \\ k_R \end{bmatrix} + \begin{bmatrix} h_1 & h_2 & \dots & h_8 \end{bmatrix} \begin{bmatrix} F_F \\ F_{Dil} \\ \cdot \\ \cdot \\ \cdot \\ W_s \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} Dx_k = \begin{bmatrix} A \\ C \end{bmatrix} x_k + \begin{bmatrix} 0 & B \\ -I & D \end{bmatrix} \begin{bmatrix} y_k \\ u_k \end{bmatrix} \tag{9}$$

$$P(z) \begin{bmatrix} x_k \\ y_k \\ u_k \\ e_k \end{bmatrix} = \begin{bmatrix} E_* - zI & -A_* & B_* & C_* \\ E_0 & -A_0 & B_0 & I \end{bmatrix} \begin{bmatrix} x_k \\ y_k \\ u_k \\ e_k \end{bmatrix} = 0 \tag{10}$$

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