Residual Bond Graph Sinks for Numerical Evaluation of Analytical Redundancy Relations in Model Based Single Fault Detection and Isolation

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Abstract— **The paper proposes a bond graph approach to model based fault detection and isolation (FDI) that uses** *residual sinks*. **These elements couple a reference model of a process engineering system to a bond graph model of the system that is subject to disturbances caused by faults. In this paper it is assumed that two faults do not appear simultaneously. The underlying mathematical model is a Differential Algebraic Equations (DAE) system. The approach is illustrated by means of the often used hydraulic two tanks system.**

Keywords— **Bond Graph models for fault detection and isolation, analytical redundancy relations, residual sinks, DAE systems.**

I. INTRODUCTION

With regard to safety, fault detection and isolation (FDI) is crucial in the supervision and closed loop control of all kinds of industrial process engineering systems. To that end, it is clear to compare the measured behaviour of a system with a reference and to use significant deviations as indicators to possible faults in some system components. The reference can be provided by a system model. The bond graph methodology [1, 2, 3, 4] is particularly suited for modelling multidisciplinary process engineering systems [5, 6]. Moreover, bond graph modelling has been intensively and successfully used for model based fault detection and isolation [7, 8, 9, 10, 11]. In these bond graph based approaches, derivation and evaluation of so-called Analytical Redundancy Relations (ARRs) play a central role. They establish constraints between known variables and include known model parameters. When a process operates under normal mode conditions, evaluation of the constraints should reveal values within certain small error bounds. Theoretically, these values, also called *residuals*, should be zero. Values exceeding given thresholds are indicators to faults in some system components. Structural analysis of the constraint relations reveals whether faults can be isolated or not.

On the other hand, artificial, so-called *residual sinks* have been added to bond graphs in order to support the tearing of the algebraic part of a Differential Algebraic Equations (DAE) system, to solve that part and to transform the DAE system into a state space model if possible (Borutzky and Cellier [12], Borutzky [13]). In this paper, it is shown how residual bond graph sinks can also be used for the numerical evaluation of ARRs. In contrast to their use in the context of tearing, the underlying mathematical model for fault detection and isolation remains a DAE system.

The paper is organised in the following manner. The next section recalls some relevant features of model based fault detection and isolation. Section III briefly reconsiders residual sinks and section IV presents the proposed bond graph approach to the numerical evaluation of residuals of ARRs in FDI. In section V, for illustration, the approach is applied to the often used example of a hydraulic two tanks system.

The underlying DAE system has been solved numerically by means of the open source mathematics software package Scilab [14]. The paper concludes by briefly summarising the features of the proposed bond graph approach.

II. FAULT DETECTION AND ISOLATION

Fault detection and isolation starts from constraints between known variables. These relations also include known model parameters. Their numerical evaluation at each time instant reveals a residual. Under normal mode of operation it should be zero. In bond graphs, constraints are clearly indicated by junctions. Each junction contributes a continuity equation for flows or efforts respectively. By using the constitutive equations of bond graph elements and by elimination of unknown variables, ARRs may be obtained in symbolic form. The form of the set of ARRs is not unique and depends on the procedure. Moreover, algebraic dependencies indicated by causal paths in the bond graph and nonlinear constitutive relations may prevent the elimination of unknown variables. Given that unknown variables can be eliminated, then structural analysis of each equation reveals a so-called signature in terms of known variables and system component parameters. For illustration, consider the hydraulic two tanks system depicted in Fig. 1. Fig. 2 shows a causal bond graph of the system. The left hand side 0-junction provides the continuity equation for the volume flow rates:

$$0 = Q_p - Q_{C_1} - Q_{R_1} \qquad (1)$$

If the left hand side zero is replaced by a residual, res_1, and if the constitutive equations of the energy C-store and of the hydraulic resistor are inserted, then the equation reads:

$$\mathrm{res}_1 = Q_p - C_1 \dot{p}_1 - k_1 \mathrm{sign}(p_1 - p_2)\sqrt{|p_1 - p_2|} \quad (2)$$

Since the right hand side includes only known variables and known parameters, the equation clearly is an ARR. In this relation, tank 1, T_1, contributes the parameter C_1 and the valve, V_1, between both tanks the parameter k_1. From this view of ARRs, an occurrence matrix can be set up with one row for each known variable or component parameter and one column for each residual. If the occurrence of a variable or a parameter in an ARR is indicated by '1' and its absence by '0', then the result is a binary matrix. This matrix is usually augmented by two other columns. The first one with the heading D indicates whether a fault can be detected. The second additional column with the heading I indicates whether a fault can be isolated [8]. If this is feasible, then it is marked by '1' otherwise by '0'. A fault can be detected if there is at least one non-zero entry in that row.
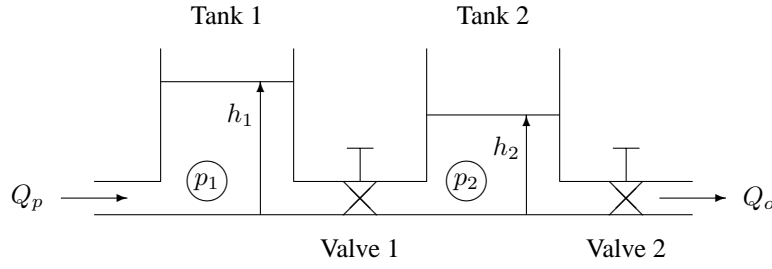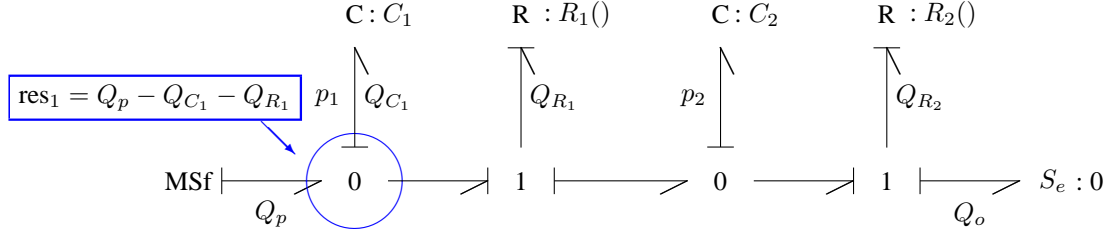
Fig. 1: Hydraulic two tanks system

Fig. 2: Bond graph of the hydraulic two tanks system

Component	Variable/Parameter	res_1	res_2	D	I
Pump	Q_p	1	0	1	0
	p_1	1	1	1	0
	p_2	1	1	1	0
Tank 1	$C_1 = A_{T_1}/(\rho g)$	1	0	1	0
Tank 2	$C_2 = A_{T_2}/(\rho g)$	0	1	1	0
Valve 1	$k_1 = c_d A_{V_1}\sqrt{2/\rho}$	1	1	1	0
Valve 2	$k_2 = c_d A_{V_2}\sqrt{2/\rho}$	0	1	1	0

TABLE I: Fault signature matrix of the two tanks systems

Fig. 3: Representation of a residual flow sink according to Bos 1986

This is indicated by '1' in the first additional column, otherwise by '0'. The augmented matrix is called *fault signature matrix*. Its columns are called fault signatures (of the ARRs of the residuals). Table I shows the fault signature matrix of the hydraulic two tanks system. The fault signature matrix of the two tanks system shows that none of the faults can be isolated. In fact, if, for a given time instant t, for instance, only residual res_2 is above a given threshold, the reason may be either a leakage from the second tank or a fault in its outlet valve V_2. Clearly, a single fault can be located (isolated), if it can be detected and if the pattern of non-zero entries in the corresponding row of the matrix is unique.

Furthermore, the fault signature matrix includes only two residuals although also each 1-junctions in the bond graph contributes a continuity equation for the efforts. However, their signature turns out to be identical to those already listed in the fault signature matrix. Thus, there are only two *structurally* independent residuals in the bond graph model of the two tanks system. In fact, consider, for instance, the sum of efforts at the 1-junction representing the volume flow rate, Q_{R_1}, through valve 1 between the two tanks. If the pressure drop across valve 1 is expressed by the known volume flow rate of the pump, Q_p, and the pressure in the first tank, T_1, then the residual, res_3, of this 1-junction reads:

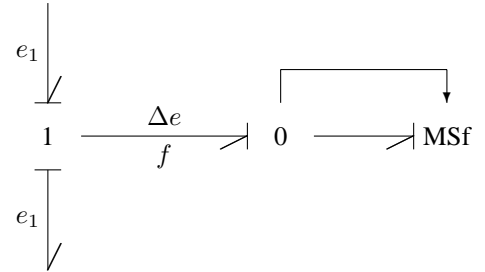$$0 = p_1 - p_2 - \frac{1}{k_1^2}(Q_p - C_1\dot{p}_1)^2\text{sign}(Q_p - C_1\dot{p}_1) = res_3 \tag{3}$$

Clearly, the signature of res_3 is structurally identical to the one of res_1. Consequently, it is of interest to derive a minimal number of structurally independent residuals from a bond graph model of a process engineering system.

III. RESIDUAL BOND GRAPH SINKS

A *residual* bond graph sink is a sink that adjusts its output power variable so that the power conjugated variable into the sink vanishes. Fig. 3 shows a graphical representation introduced by Bos [15]. It explicitly depicts the internal modulation of the sink. In this case, the difference of efforts, Δe, into the sink is sensed. It controls the output of the sink, f, such that the difference, Δe, vanishes. The difference Δe can be considered the residual of the 1-junction. For brevity we will denote residual sinks by *rSf* or *rSe*, respectively. They can be used for different purposes, e. g., for representing internal constraint forces or moments in bodies [15, 4], or for indicating tearing variables in bond graph models (Borutzky [13]). In Karnopp's all derivative causalities approach to the derivation of Lagrange equations, residual flow sources indicate generalised coordinates. In that context they are know as artificial flow sources [16]. Furthermore, in [17], Gawthrop and Smith used residual sources for a modification of the standard sequential causality assignment procedure (SCAP) in the case of bond graphs with algebraic loops.

A residual sink results if the parameter of an energy store is assumed to tend to zero. A linear inertia in integral causal-

ity with inertance I, for instance, provides a flow such that

$$I \cdot \dot{f} = \Delta e \qquad (4)$$

For $I \to 0$, the constitutive equation of the I energy store turns into the trivial equation $0 = \Delta e$ Now, the flow is no longer the output variable of an I energy store. It is not a state variable anymore. It is rather a variable determined by the algebraic equation $0 = \Delta e$. As the derivative of f has vanished, while f itself is still an unknown, the mathematical model is a DAE system of index ≥ 1 and the flow f can be considered a component of a descriptor vector. The use of residual sinks can also be related to the method of singular perturbation. In the state equations of perturbed systems, the derivative of a fast component is multiplied by a parameter ϵ of very small value. Letting $\epsilon \to 0$, the ODEs turn into a DAE system.

IV. USING RESIDUAL BOND GRAPH SINKS FOR NUMERICAL EVALUATIONS OF ARRS

Fault detection and isolation is based on the comparison of the actual behaviour of a process engineering system with that of a reference model. Signals from the real engineering process can be obtained by means of sensors and can be fed into the reference model. However, the deliberate introduction of faults into the real process for test purposes may lead to hazardous situations, to periods of process instability if the equipment allows for introduction of faults at all. Therefore, it is obvious to replace the real process by a behavioural model which enables to introduce all kinds of faults without risk. In an offline simulation, the equations of the process model and of the reference model are solved simultaneously and residuals of ARRs, being indicators for faults, are numerically evaluated. This approach, as has been proposed recently by Medjaher and his co-authors [10], has the advantage that there is no need for elimination of unknown variables from continuity equations in order to obtain ARRs, because a set of equations determining residuals is solved numerically. In general, non-linearities may even prevent the generation of ARRs in symbolic form. In contrast to the method in [10], this paper proposes to couple the process model to the reference model by means of residual sinks introduced in the previous section. Both bond graph models retain *integral* causality as the *preferred* causality. Signals from the process model control modulated sources. Their values are compared with corresponding values from the reference model. The process model is subject to faults due to external sources that can be switched on and off. If no faults are introduced into the process model, then the difference between 'measured' signals and their corresponding reference is equal to zero. This difference is input into the residual sinks. If it vanishes, the output of a residual sink is equal to zero. However, if a process variable differs from its reference due to a fault introduced into the process model, the residual sink provides a flow or an effort, respectively in order to adapt the reference model's behaviour to the perturbed process behaviour and to force the difference to zero. This non-zero output of a residual sink is a residual of an ARR and a numerical indicator to a fault. As each junction in the reference model represents a constitutive equation for efforts or flows, respectively, each

junction could, in principle, be connected to a residual sink. However, as we already know from section II, residuals may be structurally dependent. Only a subset of them will be needed to build the fault signature matrix. Causal paths between residual sinks will indicate these dependencies. In the next section, this approach is illustrated by means of the often used hydraulic two tanks system.

V. A HYDRAULIC TWO TANKS EXAMPLE

In Fig. 4, the lower part of the overall bond graph represents the process model accounting for faults. The modulated flow sinks, attached to the 0-junctions, model possible leakage from the tanks, which means that the area of the bottom of the tanks is reduced for some period of time. Representation of the valves by modulated resistors enables to model a blockage of the valves. It is assumed that the pressures in the two tanks are 'measured'. Accordingly, signal arrows are attached to the 0-junctions. The upper part of the overall bond graph represents the reference model. Both bond graphs are coupled by means of residual sinks (highlighted in red). The right hand side residual effort sink is depicted in grey because it is redundant in the sense that it contributes no fault signature different from those of the other two residuals. Therefore, the residual effort sink is not taken into account in the following. The output of a residual sink, in fact, is a residual of an ARR of a junction. For instance, summing to zero all flows at the left hand-side 0-junction of the reference models yields:

$$\begin{aligned}
f_1 &= Q_p - C_1 \dot{p}_1 - Q_{R_1} \\
&= Q_p - C_1 \dot{p}_1 - k_1 \mathrm{sign}(\mathrm{p}_1 - \mathrm{p}_2)\sqrt{|\mathrm{p}_1 - \mathrm{p}_2|} \quad (5)
\end{aligned}$$

This relation includes only known variables and known parameters and thus, is an ARR.

The two tanks system has been simulated by means of the open source mathematics package Scilab [14]. Formulation of the underlying DAE system in Scilab's mathematical input language is straightforward. The equations can be directly derived from the bond graph of Fig. 4. The Scilab function, **f**, of the DAE system of the two tanks models coupled by residual sinks is displayed in Fig. 5. The constitutive equations of the energy stores and the equations of the residual sinks have been written in implicit form. The descriptor vector is

$$\mathbf{x} = [p_1, p_2, \tilde{p}_1, \tilde{p}_2, f_1, f_2]^T$$

and the DAE system is of the form

$$\mathbf{A}\dot{\mathbf{x}} + \mathbf{g}(\mathbf{x}) = (1, 0, 1, 0, 0, 0])^T [Q_p] , \qquad (6)$$

in which **A** is a 6×6, constant coefficient singular matrix and **g** a vector function that is nonlinear due to the nonlinear constitutive equations of the orifices. As there are no differential equations for the residuals, f_1, f_2, the last two rows in **A** vanish. The DAE system is of index ≥ 1.

For the numerical solution of DAE systems, Scilab provides the widely used DASSL code [18]. In order to facilitate the specification of a consistent set of initial conditions, it is assumed that the tanks are empty at initial time $t = 0$ and that the pump delivers a constant volume flow rate, Q_p, for $10.0s \leq t \leq 40.0s$. That is, the empty tanks are filled
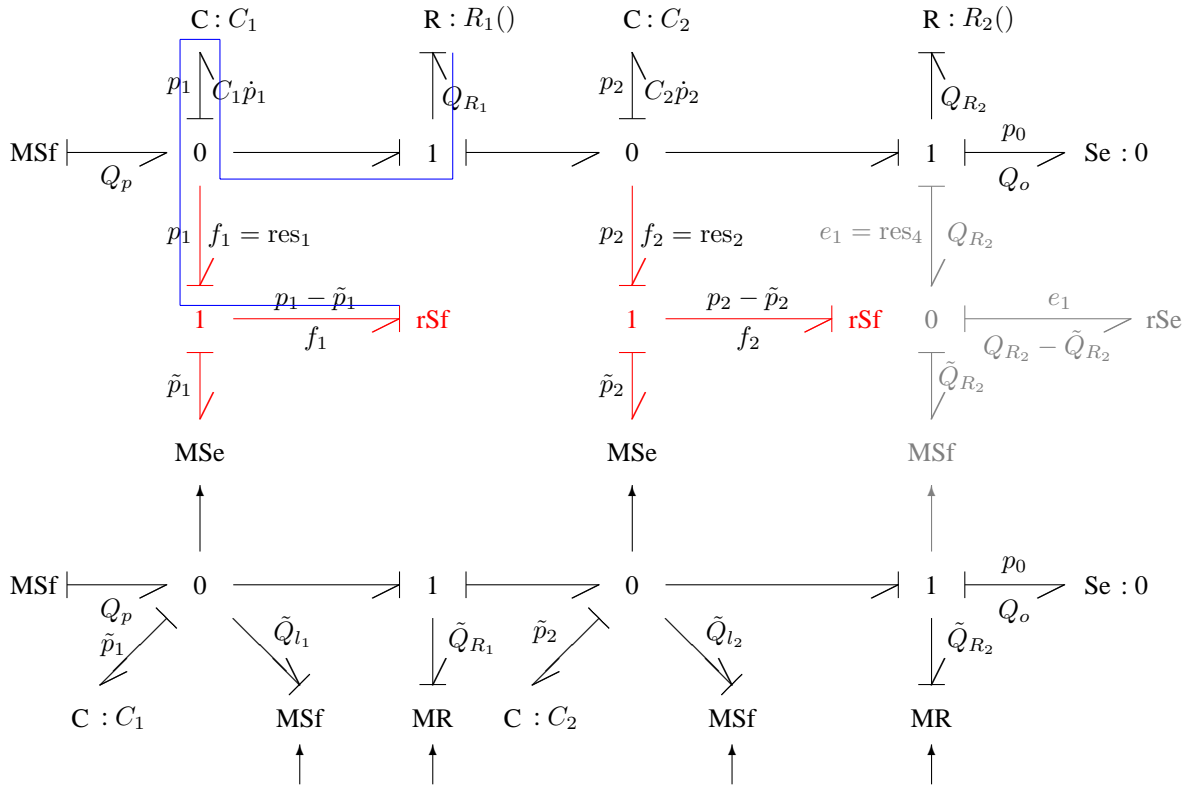
Fig. 4: Coupling of the process model subject to faults (lower part) and the reference model (upper part) by means of residual sinks
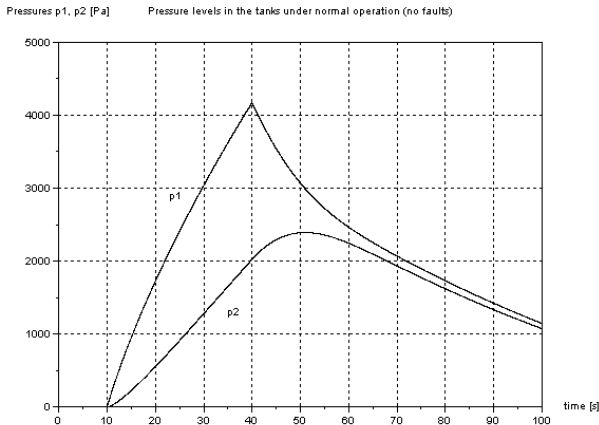

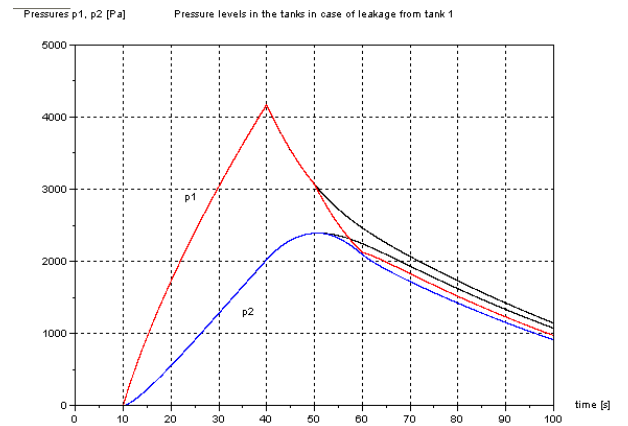Fig. 6: Pressure levels in the tanks in case of no faults

Fig. 7: Time history of the tank pressures in case of a leakage from tank 1

for 30s and then they discharge at a rate depending on how much the valves are open. Fig. 6 depicts the undisturbed dynamic behaviour. As a first scenario, a constant leakage flow from tank 1 is assumed to be effective for the time period $50s \leq t \leq 60s$, while the tanks discharge. As a result, the pressures in the tanks decrease at a higher rate during this time period. Fig. 7 shows the time evolution of the tank pressures in the case of a leakage from tank 1. A leakage from tank 1 corresponds to a decrease of the area of its bottom. According to the fault signature matrix, residual res_1 is affected, while residual res_2 is not. Figures 8 and 9 depict the residuals f_1 and f_2. Another fault that may occur is a partial blockage of the valve between the two tanks. If it happens after the pump has switched off, then, during the time period this fault is effective, the pressure in the first
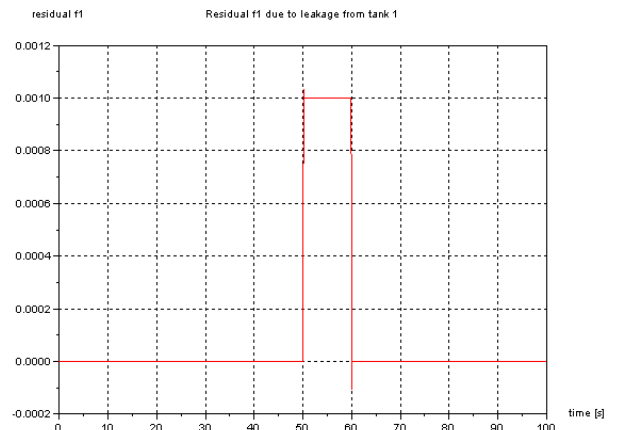

Fig. 8: Residual f_1 in case of a leakage from tank 1

```
// Scilab function with the DAE system of the two tanks models
// coupled by residual sinks
function [res, ires] = daesys(t,x,xdot)

// tank pressures of the reference model:
p1   = x(1)
p2   = x(2)
// tank pressures of the process model subject to faults:
tp1  = x(3)
tp2  = x(4)
// residuals:
f1   = x(5)
f2   = x(6)

// xdot: rate of change of the descriptor vector x:
dp1  = xdot(1)
dp2  = xdot(2)
dtp1 = xdot(3)
dtp2 = xdot(4)

// system inputs:
Qp   = Flow*pulse(t,tstart,tstop)

// no leakage from the tanks of the process model:
tQl1 = 0.0
tQl2 = 0.0

// orifices:
QR1  = orifice(AV1,p1,p2)
QR2  = orifice(AV2,p2,p0)

// partial blockage of valve 1 for 50.0s <= t <= 60.0s:
tQR1 = (1.0 - pulse2(t,50.0,60.0,0.8))*orifice(AV1,tp1,tp2)
tQR2 = orifice(AV2,tp2,p0)

// energy stores:
res(1) = Qp - QR1 - C1*dp1 - f1              // p1
res(2) = QR1 - QR2 - C2*dp2 - f2             // p2
res(3) = Qp - tQR1 - tQl1 - C1*dtp1          // tp1
res(4) = tQR1 - tQR2 - tQl2 - C2*dtp2        // tp2

// equations of the residual sinks:
res(5) = p1 - tp1                            // f1
res(6) = p2 - tp2                            // f2

ires = 0
endfunction
```

Fig. 5: Scilab function with the DAE system of the two tanks models coupled by residual sinks
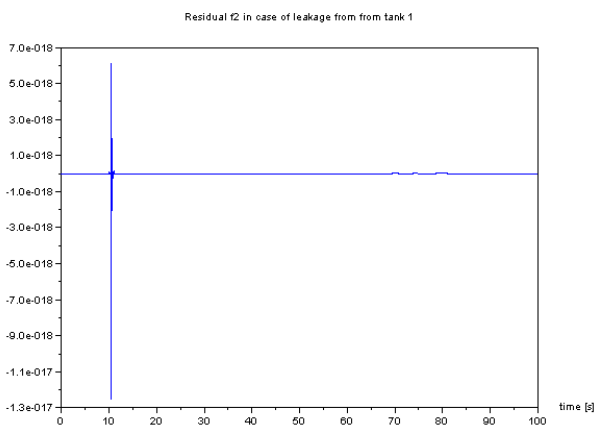

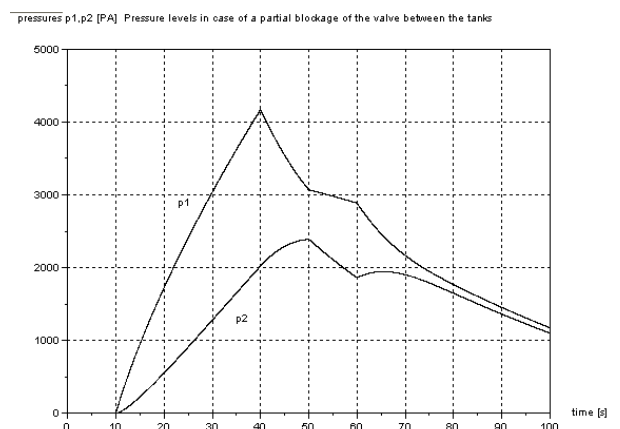Fig. 9: Residual f_2 in case of a leakage from tank 1

Fig. 10: Pressure levels in the two tanks in case of a partial blockage of the valve between the tanks

tank decreases at a lower rate, while the pressure in the second tank decreases at a higher rate. This can be seen from Fig. 10. According to the fault signature matrix both residuals are sensitive to a fault in valve 1 connecting both tanks.

This is verified by Fig. 11. Finally, Fig. 12 shows the numerical values of the residual f_2 for the cases of leakage from tank 2 and a partial blockage of valve 2. In accordance with the fault signature matrix, residual f_2 is sensitive to these
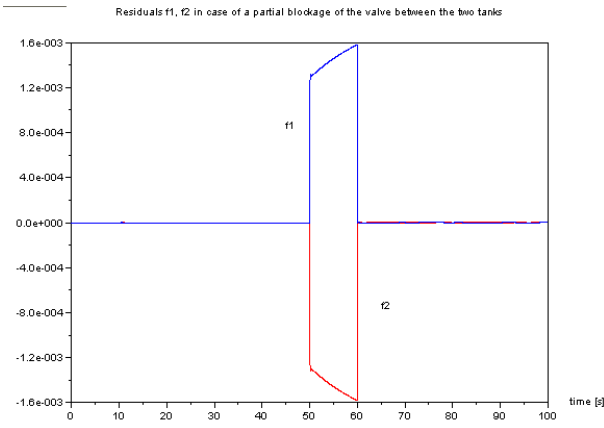
Fig. 11: Residuals f_1 and f_2 due a partial blockage of the valve between the tanks
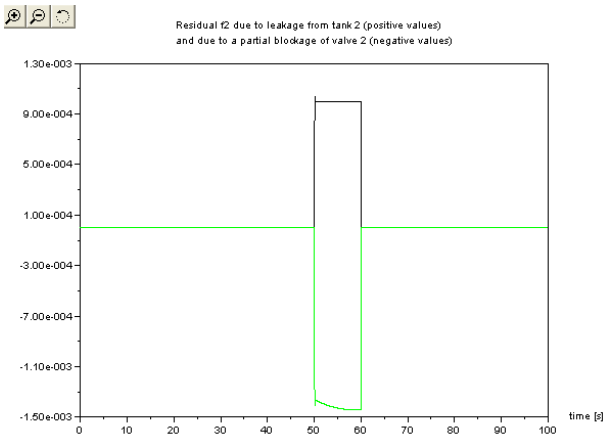

Fig. 12: Residual f_2 due to leakage from tank 2 (positive values) and a partial blockage of valve 2 (negative values)

faults.

VI. DIRECT DETERMINATION OF FAULT SIGNATURES FROM THE BOND GRAPH

Computation of the two models coupled by means of residual sinks provides numerical values for the residuals of the ARRs as has been illustrated in the previous section. Moreover, analysis of signal forward paths in the reference model part can directly reveal the entries in the fault signature matrix [11]. In fact, there is, for instance, a causal path between the resistor of valve 1 and the residual sink providing res_1, which can be indicated by the sequence of power variables involved:

$$R_1 \rightarrow Q_{R_1} \rightarrow C_1\dot{p}_1 \rightarrow C_1 \rightarrow p_1 \rightarrow (p_1 - \tilde{p}_1) \rightarrow rSf \rightarrow f_1$$

(Fig. 4). In other words, the volume flow rate Q_{R_1} through valve 1 depending on the valve's cross sectional area contributes to the sum of flows at the left-side 0-junction. Consequently, valve 1 contributes a non-zero entry to the signature of the ARR of residual res_1 and, for the reason of symmetry, also a '1' to the signature of the ARR of residual res_2. Furthermore, there are causal paths between a C energy store and a residual sink, e. g.:

$$C_1 \rightarrow p_1 \rightarrow (p_1 - \tilde{p}_1) \rightarrow rSf \rightarrow f_1$$

This is an indication that tank i contributes a non-zero entry to the signature of the ARR of residual res_i, $(i = 1, 2)$. From the fault signature matrix in Table I we already know that p_2 also contributes to the signature of the ARR of residual res_1. In fact, there is a causal path between the C energy store of the second tank and the resistor of valve 1. The output of this resistor, Q_{R_1}, is part of the sum of all flows at the left-side 0-junction. Consequently, the pressure p_2 contributes to the ARR of res_1. By this way, all non-zero entries in the fault signature matrix can be identified directly from the reference model part of the overall model.

Finally, Fig. 4 shows that the output of the right hand side residual effort sink, $e_1 = res_4$, is converted into the volume flow Q_{R_2}, which in turn contributes to the sum of flows at the 0-junction representing the pressure p_2 in the tank T_2. That is, residual res_4 depends on res_2. In fact, the constitutive equation of the outlet valve of tank T_2 reads:

$$Q_{R_2} = k_2\text{sign}(p_2 - res_4)\sqrt{|p_2 - res_4|} \qquad (7)$$

On the other hand, the sum of flows at the 0-junction representing p_2 yields:

$$\begin{aligned} Q_{R_2} &= Q_{R_1} - C_1\dot{p}_2 - res_2 \\ &= k_1\text{sign}(p_1 - p_2)\sqrt{|p_1 - p_2|} - C_1\dot{p}_2 - res_2 \end{aligned} \qquad (8)$$

Hence, res_4 provides no fault signature different from the one of residual res_2. It is redundant and can be omitted.

VII. CONCLUSIONS

Model based fault detection and isolation builds on the comparison of data from a process engineering system with data from a reference model. However, the introduction of faults into a real world process for test purposes can be impossible or unwanted for various reasons. This suggests to replace the real process by a model that can include all kinds of faults that are of interest at no risk. This paper proposes to retain preferred *integral* causality in both models and to couple them by means of *residual* sinks that have been in use for various other purposes also. These artificial elements play a clear and intuitive role. They provide an effort or a flow that forces the difference between a monitored variable and its reference to zero and that adapts the reference to the signal perturbed by a fault. At the same time, the output of the residual sink is a residual of an ARR. Simulation of the two process models coupled by residual sinks enables a numerical evaluation of the residuals of ARRs. For computation of the underlying DAE system determining the residuals, the well known DASSL code can be used. Simulation experiments have shown that parameters controlling the numerical integration should be chosen with care. For instance, in case the Jacobian matrix has not been provided in symbolic form, values for absolute and relative error tolerances, that have been chosen too small, can lead to a failure of the computation. Such problems with the numerical solution of DAE systems are well known. On the other hand, in the simulation experiments carried out, numerical errors clearly have shown to be orders of magnitude smaller than the values of the residuals so that the latter could be clearly distinguished from numerical errors. As the model including faults represents the real world process, values of 'monitored' process variables can be superimposed by noise before they are

used as an input into a residual sink. While algebraic loops and non-linearities in a model may prevent the generation of ARRs in *symbolic* form, numerical solution of DAE system determining the residuals of ARRs is mostly feasible. Moreover, inspection of the reference model part with regard to causal paths ending at residual sinks enables to set up the fault signature matrix directly from the bond graph, i. e., equations do not need to be formulated and manipulated.

The two process models coupled by residual sinks can serve for the analysis of various fault scenarios. One advantage of using a model for the faulty real process is that signals from the simulated process may be obtained much quicker than in real time.

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APPENDIX

```
// Parameters of the two tanks example
g    = 9.81; // [m/s^2]
// Oil density:
rho  = 780.0; //[kg/m^3]
// Discharge coefficient:
c_d  = 0.61;
r    = c_d*sqrt(2/rho);
//
// Cross sectional area of tanks:
AT1  = 1.53e-1; // [m^2]
AT2  = AT1;
// Capacitances of tanks:
C1   = AT1/(rho*g);
C2   = C1;
// Cross sectional area of valves:
AV1  = 0.2e-2; // [m^2]
AV2  = 0.1e-2; // [m^2]
//
// flow of the pump:
Flow = 0.5e-2; // [m^3/s]
//
// Leakage from tank T_1:
Ql = 0.1e-2; // [m^3/s]
//
// pressure of the environment:
p0 = 0.0; // [Pa]
//
//Initial conditions:
//
// tanks are empty at t=t0;
// no flows into and out of the tanks at t=t0:
y0 = [0.0;0.0;0.0;0.0;0.0;0.0];
ydot0 = [0.0;0.0;0.0;0.0;0.0;0.0];
```

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