Unmeasured Variable Fault Diagnostics using Engineering Models

This document provides some background and examples about how to properly implement Primary models and Performance Equations in FALCONEER IV™ applications. Specifically it discusses the use of unmeasured variables and global variables (parameters) in those constraints for describing normal operating behavior.

Accurately specifying normal process behavior with a linearly independent set of Primary models is the key configuration step of a FALCONEER IV™ application. These models must depend upon at least one measured variable and any number of unmeasured variables or parameters, as long as these unmeasured variables or parameters can be adequately characterized by a normal and/or extreme value under normal operation for all the possible process operating regimes on which the program will perform Sensor Validation and Proactive Fault Analysis (SV&PFA).

A simple example of such an unmeasured variable is to assume the absence of a leak(s) when creating a mass balance. Two examples would be:

1) A process leak measured in GPM. Normally the flow rate of that leak is 0 GPM.

   0 = FlowIn – FlowOut - PipeLeak

2) A simple mixing tee. Two steams converge to form a combined stream. The following mass balance can be derived if both inlet stream densities are the same:

   0 = (Flow1 – Leak1) + (Flow2 – Leak2) – (Flow3 + Leak3)

   Where:
   - Flow 1 and Flow 2 are the inlet stream sensors
   - Flow 3 is the combined stream sensor
   - Leak 1 is an unmeasured leak in the process downstream of the Flow1 sensor but upstream of the mixing tee (normal value is 0 GPM);
   - Leak 2 is an unmeasured leak in the process downstream of the Flow2 sensor but upstream of the mixing tee (normal value is 0 GPM);
   - Leak 3 is an unmeasured leak in the process downstream of the mixing tee but upstream of the Flow 3 (normal value is 0 GPM)

If all of the dominant flow streams in the process are known and either directly measured or inferable, the mass balance will close with the leak(s) unmeasured variable(s) set to a normal and extreme value of 0. For a pressurized system, any leak(s) would be greater than 0 so this (these) unmeasured variable(s) could only deviate from its (their) normal, extreme value higher than 0. This is how such unmeasured variables would be implemented. The residual of the mass balance would be directly related to the magnitude of the leak(s) in such fault situations. This is because such leak variables are known in our patented Method of Minimal Evidence (MOME) terminology as linear assumptions of their corresponding Primary models.

Now consider the aforementioned mass balance when converting measured volumetric flows into mass flows (the actual conserved entity). This is accomplished by multiplying each flow stream by its corresponding density. For most liquids this is a parameter that can be adequately characterized by a constant, normal value. If there is absolutely no possible way for contamination by another flow stream, nor that another fluid could be flowing through that flow stream meter, nor that multiple phase flow is occurring, then this density can be implemented as a global variable and neither of these possible faults will be considered by the fault analyzer. If not, then it has to be implemented as an unmeasured variable that can fail in whichever direction is (are) possible for this (these) non-normal (i.e., faulty) operation(s).

Other possible ways are available to detect faults with unmeasured variables. An example of one is for detecting vacuum leaks in a crystallizer. Using the Antoine Equation as an equation of state to relate mother liquid temperature to operating vapor pressure constitutes a Primary model.

$$0 = Temp - (B / (A - LOG10(Leak * Press))) + C$$

Where:

- Temp is the System Temperature
- Press is the System Pressure
- A, B, C are the Antoine Equation constants for the vapor in the system
- Leak is an Unmeasured variable (dimensionless) and has a normal value of 1.0

Its beta is a direct measure of normal boiling point elevation of the mother liquid. Vacuum leaks can be directly detected whenever the vapor pressure is higher than predicted by the Primary model. An unmeasured variable can be multiplied to the pressure term in the Primary model and set to a value of 1.0 for situations of no vacuum leaks. Whenever the actual pressure rises above its predicted value, the vacuum leak fault would be diagnosed as a possible explanation if the corresponding unmeasured variable was configured as could fail low. However, the residual of the Primary model would not be directly related to the magnitude of the vacuum leak in such fault situations. This is because such vacuum leak variables are known in MOME terminology as continuous non-linear assumptions of their corresponding Primary models.

Valid Primary models can range from having a very fundamental basis (derived from conservation principles, actual controller equations, etc.) to being semi-empirical (valve and pump curves, equations of state, etc.) to being accepted correlations that consistently relate groups of measured and unmeasured variables. It is always better to derive the most fundamental constraint relationships possible because they typically require fewer modeling assumptions to describe normal operating behavior, improving the resolution of the subsequent fault analysis. Furthermore, their residuals tend to have smaller variances so that smaller magnitudes and/or rates of occurrence of actual faults are capable of being diagnosed. As a general rule, depending upon only the particular variables being measured and the frequency at which they are measured, the most rigorous basis should be used to derive all Primary models. This allows the most fundamental understanding of the underlying normal process operation to be continuously utilized for monitoring and analyzing any abnormal process operation.

Normal operating behavior of the actual process system can also be modeled using Performance Equations. These typically are models that have one unmeasured variable that cannot be adequately characterized with a normal and/or extreme value during normal operating conditions. Basically this is a situation of having one equation with one unknown variable, thus the equation can be solved to generate an estimate of the actual value of the unmeasured variable. These unmeasured variables can be physically significant such as determining heat transfer efficiency, overall reaction conversion, actual pump efficiency, etc. Their calculated values, given that the other measured and unmeasured variables used to calculate them are all valid, can then be used to gauge operating performance of their associated process units (hence the name Performance Equations). Alarms are given whenever validated calculations of these parameters deviate from normal or acceptable operating zones predetermined for them. Relentlessly performing these calculations and analyzing the results maximizes the time available to the process operators to make corrective action or schedule restorative maintenance.

Examples of Primary Models with Unmeasured Variables

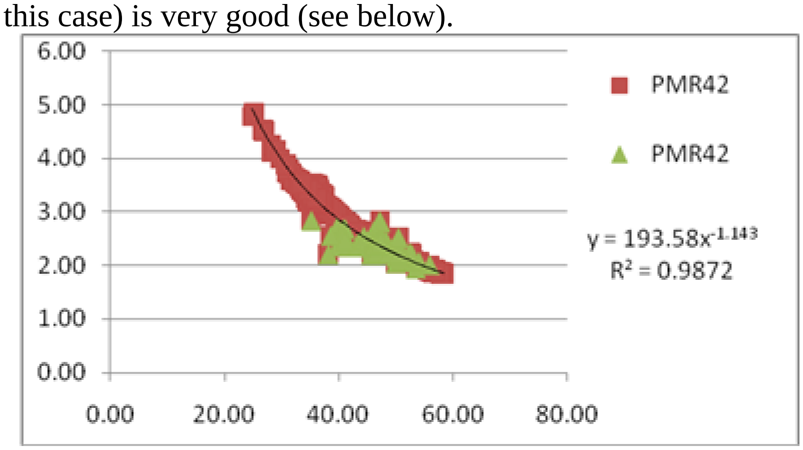
The following model examples demonstrate a variety of ways unmeasured variables can be incorporated into Primary models and Performance Equations.

Example 1: Turbine Seal Leak (Designed based Performance Model)

P1	Stage outlet pressure (measured variable)
P2	Stage inlet pressure (measured variable)
L1	Leak in Seal between Higher Pressure and Lower Pressure (unmeasured variable, normal value = 1.0, can only fail high)
C1, C2	Performance Curve Coefficients (constant parameters derived from actual normal turbine operation)

P1 $0 = (P1 * L1) / P2 * C1 - C2$

This example (although not based on a first principle model but turbine design and operation knowledge) for turbine diagnostics would be an internal seal leak because in this case the "empirical" correlation based actual process behavior over a wide range of production (power generation in this case) is very good (see below).



Example 2: Standard Pump Curve (Flow versus Head)

- F — Flow from Pump (measured variable)
- L — Leak between Pump and Flow meter (unmeasured variable, normal value = 0.0, can only fail high)
- Pi — Pump inlet pressure (measured variable)
- Po — Pump outlet pressure (measured variable)
- PE — Pump Efficiency at current operating conditions (unmeasured variable, normal value = 100.0, can only fail low to be between range of 0.0 – 100.0)
- A, B, C — Pump Curve Coefficients (constant parameters derived from actual normal pump operation)

P2 0 = F - L - (PE/100.0) * (A – B *(Po –Pi) – C *((Po – Pi)^2))

Flow rates calculated with the pump curve would over estimate the actual flow in situations when the pump was operating abnormally (say cavitating).

Example 3: Standard Valve Curve (Flow versus valve position (as correlated to Controller Output))

- F — Flow through valve (measured variable)
- L — Leak between Valve and Flow meter (unmeasured variable, normal value = 0.0, can only fail high)
- CO — Controller Output % (measured variable) (valve position, assumes air to open; ranges between 0.0 - 100.0 and cannot fail)
- Pu — Stream pressure upstream of valve (measured variable)
- Pd — Stream pressure downstream of valve (measured variable)
- Vblock — Valve “Efficiency” or Blockage at current operating conditions (unmeasured variable, normal value = 100.0, can only fail low to be between range of 0.0 – 100.0 when valve is partially blocked)
- Vstuck — Flow through the stuck valve (unmeasured variable; normal value = 0.0; can fail high or low)
- A, B — Valve Curve Coefficients (constant parameters derived from actual normal valve operation)

P3 0 = F - L - (Vblock/100.0)*(A * (CO) + B * (CO^2))*((Pu – Pd)^1/2) - Vstuck

If the valve is stuck, a PI or PID controller would max out its CO output to either 0.0 (case when measured F is higher than flow setpoint) or 100.0 (case when measured F is lower than flow setpoint). A similar outcome occurs if the flow meter is stuck. Valve curves can also be derived without the measured pressure drop (missing either the feed pressure or the process pressure (also make them unmeasured variables themselves with estimated constant values and the ability to fail both high and low) or a constant normal pressure drop). In this latter case the model would be simplified to be:

P3p $0 = F - L - (Vblock/100.0) * (Ap * (CO) + Bp * (CO^2)) - Vstuck$

Ap, Bp Valve Curve Coefficients (constant parameters derived from actual normal valve operation) at various normal pressure drops

The variance on Primary model P3p would normally be larger than the more accurate Primary model P3.

Example 4: Validation and Fault Diagnostics - Example of a Soft Sensor / Inferential Sensor / Performance Equation / Key Performance Indicator (KPI) –

Consider a typical heat exchanger. If the energy balance derived below **(Primary Model P_4)** was the only primary model depending upon each of its entire set of assumptions, then the distinct rule set for this system would be as follows:

P_4

$$0 = (F_{P\,I} - Lp) * cp_{P} * (T_{P\,i} - T_{P\,o}) - \exp(P_{FAIL}) * (Peff / 100.0) * (F_{Wex} + Lw) * cp_{W} * (T_{W\,o} - T_{W\,i}) * (L_{TUBES}) - M_{Wex} * cp_{W} * [\delta(T_{W\,o}) / \delta(time)]$$

Assumptions for Primary Model P_4:

1) Linear – FPi (process stream flow rate into HTX) flow sensor is correct (measured variable)
2) Linear – TPi (process stream temp. into HTX) thermocouple reading is correct (measured variable)
3) Linear – TPo (process stream temp. out of HTX) thermocouple reading is correct (measured variable)
4) Linear – TWi (water stream temp. into HTX) thermocouple reading is correct (measured variable)
5) Linear – TWo (water stream temp. out of HTX) thermocouple reading is correct (measured variable)
6) Linear - cpp (heat capacity of process stream) is known and constant is correct (unmeasured variable) set to normal value or global variable formula; can fail high or low
7) Linear - cpw (heat capacity of water stream) is known and constant is correct (unmeasured variable) set to normal value or global variable formula; can fail high or low
8) Linear - Mwex (mass of water in shell side of HTX) is known and constant is correct (unmeasured variable) set to actual exchanger volume; can fail low only
9) Linear – Lp (no process leaks anywhere other than HTX tubes is correct) (unmeasured variable) set to normal value of 0.0; can fail high only
10) Linear – L_{TUBES} no process leaks in HTX tubes (unmeasured variable) set to normal value of 1; can fail high or low (leak into tube-side or into shell-side)
11) Linear – Lw (no cooling water leaks anywhere other than HTX Tubes) (unmeasured variable) set to normal value of 0.0; can fail high only
12) Linear – Peff (no gradual decrease in the cooling water pump efficiency) (unmeasured variable) set to normal value of 100.0; can fail low only

The following Soft Sensor or Inferential Sensor or Performance Equation (PE) can be formulated for evaluating the actual overall heat transfer coefficient from another primary model, P_5:

P_5 $\quad 0 = (F_{P\,I} – Lp) * cp_{P} * (T_{P\,i} - T_{P\,o})$
$\quad - U_{act}*A* (((T_{P\,i} - T_{W\,o}) - (T_{P\,o} – T_{W\,i})) / \ln((T_{P\,i} - T_{W\,o}) / (T_{P\,o} – T_{W\,i})))$

And upon rearranging

PE_1 $\quad U_{act} = (F_{P\,I} – Lp) * cp_{P} * (T_{P\,i} - T_{P\,o}) / A* (((T_{P\,i} - T_{W\,o}) - (T_{P\,o} – T_{W\,i})) / \ln((T_{P\,i} - T_{W\,o}) / (T_{P\,o} – T_{W\,i})))$

where: U_{act} = calculated overall heat transfer coefficient from current actual process measurements
(Unmeasured variable in P_5 or Performance Equation in PE_1)

A = actual heat transfer area of Shell & Tube heat exchanger
(global variable with a known, constant value which never changes)

The following are examples of the possible patented Sensor Validation & Proactive Fault Analysis (SV&PFA) rules in such a situation:

Data Validation Rule (based on assumptions 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 above):

$P_4^S \Rightarrow a_1^S \wedge a_2^S \wedge a_3^S \wedge a_4^S \wedge a_5^S \wedge a_6^S \wedge a_7^S \wedge a_8^S \wedge a_9^S \wedge a_{10}^S \wedge a_{11}^S \wedge a_{12}^S$

Meaning primary model 4 is validated or satisfied **(P_4^S)** when all assumptions are validated or satisfied;

- where **a_1^S** means assumption 1 is satisfied, **a_2^S**, means assumption 2 is satisfied, etc.
- "$\wedge$" is the logical AND

Fault Analysis Rules (based on assumptions 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 above):

$P_4^H \Rightarrow a_1^H \vee a_2^H \vee a_3^L \vee a_4^L \vee a_5^H \vee a_6^H \vee a_7^L \vee a_8^L \vee a_9^H \vee a_{10}^H \vee a_{11}^L \vee a_{12}^H$

$P_4^L \Rightarrow (a_1^L \vee a_2^L \vee a_3^H \vee a_4^H \vee a_5^L \vee a_6^L \vee a_7^H \vee a_8^H \vee a_{12}^L \vee a_{13}^L) \wedge a_9^S \wedge a_{10}^S \wedge a_{11}^S$

Meaning primary model 4 is failing or significantly deviating from normal in a high direction **(**P_4^H**)** or in a low direction (P_4^L**)** based on the pattern of the assumptions shown;

- where **a_1^H** means assumption 1 is deviating high , **a_2^L**, means assumption 2 is deviating low, etc.
- "$\vee$" is the logical OR

Before a meaningful calculation of the heat transfer coefficient, or PE_1, is possible, the data required to do this calculation must be validated per the rules above. These diagnostic rules imply the sensor variables required to calculate the overall heat transfer coefficient have to be validated before a meaningful calculation can be performed with them. This preempts a situation of Garbage In, Garbage Out (GIGO) for the significance of the calculated overall heat transfer coefficient. It in effect creates a precedence hierarchy among the various SV&PFA diagnostic rules, directly specifying the order in which the diagnostic rules are checked during the subsequent fault analysis.

With this validated equation, there is now the possibility for the value of Uact to be plotted over time as process conditions change and identifying in real-time incipient fouling of the heat exchanger as it occurs. For this example, the auto-generated rule identifying the problem it would be as follows:

$a_1^S \wedge a_2^S \wedge a_3^S \wedge a_4^S \wedge a_5^S \wedge a_6^S \wedge a_9^S \wedge a_{13}^S \wedge (U_{act} < U_{fouled})$ ➔ Heat Exchanger is Fouled

where: U_{fouled} = sufficiently degraded heat transfer performance for the heat exchanger to be considered failed