ADDITION OF COMPONENTS TO RELAP5
CONTROL SYSTEM

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ABSTRACT

Four new components have been added to the RELAP5 control system: constant, proportional-integral, lag, and lead-lag. As background information, descriptions of current control components are included. Descriptions of numerics and testing for all components are included. The report concludes with recommendations for further work on the control system.

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1. INTRODUCTION

Four components, constant, proportional-integral, lag, and lead-lag, have been added to the RELAP5 control system. The complement of the unit trip component has also been added. Through various techniques, the capabilities of the new components could be simulated with the existing components. The advantages of the new components are that they allow direct input of control system components in the commonly used notation, eliminate use of several components as previously required, and allow use of better numerical techniques.

As background information, a review of existing capability is presented. In the equations that follow, Y_i is the control variable defined by the ith control component, A_j, R and S are real constants input by the user, I is an integer constant input by the user, V_j is a quantity advanced in time by RELAP5 and can include Y_i, t is time, and s is the Laplace transform variable. Superscripts involving the index n denote time levels.

2. EXISTING CONTROL COMPONENTS

The arithmetic control components are:

Summer

$$Y_i = S[A_o + A_1V_1 + A_2V_2 + \ldots]$$

Multiplier

$$Y_i = S\ V_1\ V_2\ \ldots$$

Divider

$$Y_i = \frac{S}{V_1} \text{ or } Y_i = \frac{S\ V_2}{V_1}$$

Exponentiation

$$Y_i = S\ V_1^I \quad ,$$

$$Y_i = S\ V_1^R$$

$$Y_i = S\ {V_1}^{V_2} \quad .$$

A table lookup function is

$$Y_i = S\ F(V_1)$$

where F is a function defined by table lookup and interpolation.

Standard functions are

$$Y_i = SF(V_1, V_2, V_3, \ldots)$$

where F can be $|V_1|$, $\exp V_1$, $\ln V_1$, $\sin V_1$, $\cos V_1$, $\tan V_1$, $\tan^{-1} V_1$, $V_1^{1/2}$, $MAX(V_1, V_2, V_3 \ldots)$, and $MIN(V_1, V_2, V_3, \ldots)$. Only MAX and MIN may have multiple arguments.

Trip related components are:

Unit trip $Y_i = SU\ (\pm t_r)$

Trip Delay $Y_i = ST_r(t_r)$

where t_r is a trip number and if negative indicates that the complement of the trip is to be used, U is 0.0 or 1.0 depending on trip t_r (or its complement if t_r is negative) being false or true, and T_r is -1.0 if the trip is false and the time the trip was last set true if the trip is true.

In the sequence of operations that perform a time advancement of the trip, heat conduction, hydrodynamic, reactor kinetic, and control systems of RELAP5, the control system is processed last. Thus, the end of time step (n+1) values for trip variables t_r and all V_1 variables except control variables Y_i are available. The control components are evaluated in component number order. Thus, when evaluating

$$Y_i^{n+1} \ , \ Y_k^{n+1}$$

values are available for $k < i$ and only

$$Y_k^n$$

values are available for $k \geq i$. In the example

$$Y_{10} = A_o + A_1 T^{n+1} + A_2 P^{n+1} + A_3 Y_8^{n+1} + A_4 Y_{10}^n + A_5 Y_{15}^n$$

T and P which represents a temperature and pressure from the heat structure or hydrodynamic systems are new time values, Y_8 is also a new time value because it was advanced before control component 10, and Y_{10} and Y_{15} are old time values. Use of new time values when i=k or for Y_{10} in the example is being considered.

The integral component evaluates

$$Y_i = S \int_{t_1}^{t} V_1 \, dt$$

where t_1 is the time the component is added to the system, and the initial value at t_1 is an input item.

The integral is advanced by the trapezoidal approximation,

$$Y_i^{n+1} = Y_i^n + S\left[V_1^n + V_1^{n+1}\right]\frac{\Delta t}{2} \quad .$$

Both new time (n+1) and old time (n) values are available for V_1 except when it is a control variable Y_k, $k \geq i$. For the case when $V_1 = Y_k$, $k \geq i$, the V^n and V^{n+1} are instead V^{n-1} and V^n. Use of the proper values is being considered when k=i. Also, use of

$$Y_i^{n+1} = Y_i^n + S\,V_1^n\,\Delta t$$

is being considered when $V_1 = Y_k$, $k > i$. Use of the integral component when old time values will be used should be avoided. Consider the example

$$a = P_1 - P_2 - BV - kd$$

$$V = \int a\,dt$$

$$d = \int V\,dt \quad .$$

This acceleration-velocity-distance system can not be advanced without use of old values. As a general rule, it is considered better to use the old value in the algebraic expression and not in the integral expressions.

Thus, using $Y_1 = a$, $Y_2 = V$, $Y_3 = d$

$$Y_1 = P_1 - P_2 - BY_2 - kY_3$$

$$Y_2 = \text{INT}\ (Y_1)$$

$$Y_3 = \text{INT}\ (Y_2)$$

where INT is the integral operation.

Two components provide for differentiation

$$Y_i = \frac{dV_1}{dt} \quad .$$

The DIFFERNI component evaluates the derivative by the inverse of the integration technique,

$$Y_i = \frac{2S}{\Delta t}(V_1^{n+1} - V_1^n) - Y_i^n \quad .$$

This component is not recommended since it can be unstable, requires an accurate initial value and does not recover from a bad initial value. Deletion of this component is being considered. The recommended derivative component, DIFFERND uses a simple difference expression,

$$Y_i = S\,\frac{(V_1^{n+1} - V_1^n)}{\Delta t} \quad .$$

Note that differentiation is a "noisy" process and should be avoided. Differentiation of control system variables can almost always be avoided. Filtering of the result of differentiating of other variables should be considered. Similar to the case of the integral component, old time values are used when advancement of Y_i involves $V_1 = Y_k$, $k \geq i$.

Delay

The delay component is defined by

$$Y_i = SV_1(t - t_d)$$

where t_d is the delay time. A user input h determines the length of the table used to store past values of V_1. The maximum number of time-function pairs is h + 1. The delay table time increment is t_d/h. The delayed function is obtained by linear interpolation using the stored past history. As time is advanced, new time values are added to the table. Once the table fills, new values replace values that are older than the delay time.

Initialization of control components is very similar to a time advancement. At the start of control component initialization, all other time advanced quantities have been initialized. Control component input includes an initial value and a flag which indicates if initialization is to be performed. The initialization proceeds in the order of component numbers. The initial value entered becomes the initial value if no initialization is specified. Except for integral and differential components, the initialization is simply the specified computation using the available data. If component i references Y_k, $k < i$, the initialized value of Y_k is used; if $k \geq i$, the entered initial value is used. For integral and differential components, the entered initial value is used regardless of the initialization flag.

3. NEW COMPONENTS

Constant Component

This new component sets Y_i to an input constant,

$$Y_i = S \quad .$$

Because of the constants S and A_j in the summer component, this component is seldom needed. The only situation needing this component is the standard functions MAX and MIN where one of the arguments V_j must be a constant. The only other means of specifying a V_j as a constant would be the use of an interactive input variable.

Proportional-Integral Component

This component evaluates

$$Y_i = S\left[A_1 \; V_1 + A_2 \int_{t_1}^{t} V_1 \; dt\right]$$

or in Laplace transform notation,

$$Y_i(s) = S\left[A_1 + \frac{A_2}{s}\right] V_1(s) \quad .$$

This component is advanced in time by

$$I^{n+1} = I^n + \left[V_1^n + V_1^{n+1}\right] \frac{\Delta t}{2}$$

$$Y_i^{n+1} = S\left[A_1 V_1^{n+1} + A_2 \; I^{n+1}\right] \quad .$$

The comments above concerning integration with $V_1 = V_K$ hold for this component.

If the initialization flag is off, $Y°$ is the entered initial value and

$$I^{\circ} = \frac{1}{A_2}\left[\frac{Y_i^{\circ}}{S} - A_1 V_1^{\circ}\right]$$

If initialization flag is on,

$$I° = 0$$

$$Y°_i = SA_1 \, V_1^{\circ}$$

<u>Lag Component</u>

The lag component is defined in Laplace transform notation as

$$Y_i(s) = S\left[\frac{1}{1 + A_1 \, s}\right]V_1(s)$$

Through algebraic rearrangement,

$$Y_i(s) + A_1 s Y_i(s) = S \, V_1(s)$$

$$\frac{Y_i(s)}{s} + A_1 Y_i(s) = \frac{S \, V_1(s)}{s}$$

$$Y_i(s) = \frac{S \, V_1(s) - Y_i(s)}{A_1 s} \quad .$$

Transforming to time domain gives

$$Y_i = \int_0^t [S\ V_1 - Y_i]\ dt \quad .$$

The lag component is advanced numerically by

$$Y_i^{n+1} = Y_i^n + \left[S(V_1^n + V_1^{n+1}) - Y_i^n - Y_i^{n+1}\right]\frac{\Delta t}{2A_1}$$

or

$$Y_i^{n+1} = \frac{Y_i^n\left(1 - \frac{\Delta t}{2A_1}\right) + S\left(V_1^n + V_1^{n+1}\right)\frac{\Delta t}{2A_1}}{1 + \frac{\Delta t}{2A_1}} \quad .$$

If the initialization flag is set,

$$\overset{\circ}{Y}_i = S\overset{\circ}{V}_1 \quad .$$

<u>Lead-Lag Component</u>

The lead-lag component is defined in Laplace transform notation as

$$Y_i(s) = S\left[\frac{1 + A_1 s}{1 + A_2 s}\right] V_1(s) \quad .$$

Rearranging algebraically,

$$Y_i(s) + A_2 s Y_i(s) = SV_1(s) + A_1 s\ SV_1(s)$$

$$Y_i(s) = \frac{A_1 S\ V_1(s)}{A_2} + \frac{S\ V_1(s) - Y_i(s)}{A_2 s}$$

Transforming to time domain gives

$$Y_i = \frac{A_1 S V_1}{A_2} + \int_0^t \left[\frac{S V_1 - Y_i}{A_2}\right] dt$$

The lead-lag component is advanced numerically by

$$Y_i^{n+1} = \frac{A_1}{A_2} S V_1^{n+1} + I^n + \left[S\left(V_1^n + V_1^{n+1}\right) - Y_i^n - Y_i^{n+1}\right] \frac{\Delta t}{2A_2}$$

or

$$Y_i^{n+1} = \frac{\frac{A_1}{A_2} S V_1^{n+1} + I^n + \left[S\left(V_1^n + V_1^{n+1}\right) - Y_i^n\right] \frac{\Delta t}{2A_2}}{1 + \frac{\Delta t}{2A_2}}$$

$$I^{n+1} = I^n + \left[S\left(V_1^n + V_1^{n+1}\right) - Y_i^n - Y_i^{n+1}\right] \frac{\Delta t}{2A_2}$$

If no initialization is specified, $I^\circ = 0$ and Y_i is the entered initial value. If initialization is specified,

$$Y_i^\circ = SV_1^\circ \quad , \quad I^\circ = \left(1 - \frac{A_1}{A_2}\right) SV_1^\circ$$

For both lag and lead-lag components, if $V_1 = Y_k$: $k = i$ is an error; when $k < i$, old and new values are used as indicated; if $k > i$,

V_1^n and V_1^{n+1} are really Y_k^{n-1} , Y_k^n .

4. CONTROL COMPONENT TESTING

The arithmetic type and trip related components were checked by simply hand computing the indicated operations. The integral, differential, and proportional-integral components were checked by specifying $V_1 = t$. The analytical results are:

Integral

$$Y = \frac{St^2}{2}$$

Differential

$$Y = S$$

Proportional integral

$$Y = ASt + \frac{A_2 St^2}{2} \quad .$$

The components were verified by checking that the numerical results exactly matched the analytical results. In addition, the integral result was differentiated and the differential result integrated with subsequent components, and code results checked that both yielded $y = t$.

The lag and lead-lag components were also checked using $V_1 = t$. The analytical result is

$$Y = S\left[t + (A_2 - A_1)(\exp\left[-\frac{t}{A_2}\right] - 1)\right]$$

where A_1 is the lead time constant (0 if lag component) and A_2 is the lag time constant. The numerical technique provides only an approximate solution to the analytical problem. Table 1 shows a comparison between numerical and analytical results for lag and lead-lag components. The lag time constant is 0.10 and the lead time constant is 0.05. The components were advanced with a hydrodynamic problem with no coupling between hydrodynamics and control components. Time steps were controlled by the hydrodynamics and the average time step was 0.0005 up to t = 0.01 and 0.001 for the remainder of the advancement. The agreement is good.

TABLE 1. ANALYTICAL-NUMERICAL COMPARISON FOR LAG AND LEAD-LAG COMPONENTS

Time	Analytical	Numerical	Analytical	Numerical
0.0	0.0	0.0	0.0	0.0
0.002	1.9867E-4	1.9865E-4	1.0099E-2	1.0099E-2
0.004	7.8944E-4	7.8932E-4	2.0395E-2	2.0395E-2
0.006	1.7645E-3	1.7644E-3	3.0882E-2	3.0882E-2
0.008	3.1164E-3	3.1162E-3	4.1558E-2	4.1558E-2
0.010	4.8374E-3	4.8372E-3	5.2419E-2	5.2419E-2
0.020	1.8731E-2	1.8730E-2	0.10937	0.10936
0.050	0.10653	0.10653	0.30327	0.30326
0.100	0.36788	0.36788	0.68394	0.68394
0.200	1.1353	1.1353	1.5677	1.5677
0.300	2.0498	2.0498	2.5249	2.5249
0.400	3.0183	3.0183	3.5092	3.5092
0.500	4.0067	4.0067	4.5034	4.5034

S = 10.0.

Lead time constant = 0.10.

Lag time constant = 0.05.

5. UNITS

RELAP5 operates internally with consistent SI units. With the exception of the control system, either SI or British units may be specified on input and/or output. The control system permits only SI units. Omission of British input allowed quick implementation of the control system. Initially, RELAP5 usage was primarily in SI units, but current trends show increasing use of British units, especially application to power reactors. Thus, the British units option should be provided.

Units conversion for the control system is somewhat more complex than other systems within RELAP5. Consider

$$Y_1(\text{unit1}) = A\left(\frac{\text{unit1 - sec}}{\text{lb}}\right)\ w\ \left(\frac{\text{lb}}{\text{sec}}\right) + B\left(\frac{\text{unit1 - in}^2}{\text{lb}}\right)\ P\left(\frac{\text{lb}_f}{2}\right)$$

$$+\ C\left(\frac{\text{unit1}}{R}\right)\ T(R)$$

$$Y_2(\text{unit2}) = D\left(\frac{\text{unit2}}{\text{unit1}}\right)\ Y_1(\text{unit1}) + \ldots$$

where A, B, C, and D are control system input data, w is flow rate, P is pressure, and T is temperature. Units are shown in parentheses. During input processing, A, B, C, and D must be changed so that Y_i is computed in SI units. At output, Y_i must be converted to British units. Two conversion factors must be applied: a "denominator" factor for the variable (w, P, etc.), and a "numerator" factor for the control variable. The denominator factor for W, P, etc., is easily obtained since they are defined quantities within the code and conversion factors are maintained for them. The control system variables are defined only at input and the control system input must be modified for the user to specify the units or a conversion factor. The control variable conversion factor is needed for the numerator part of the conversion, the denominator part when control variables are referenced in other control components, and output editing.

The expressions, unit1 and unit2 were used to denote that the user could use any units or that the quantity is to be considered dimensionless. An example of a dimensionless case is when direct simulation of a control system is desired and some control variables are voltage levels. However, the user must remember that if a control system variable is to be compared to other time advanced variable in RELAP5, it must be in SI units.

6. RECOMMENDATIONS

The next scheduled work on the control system is the addition of a shaft component. At that time, these additional items are recommended.

1. The DIFFERNI component be removed. Also, diagnostics should check that the DIFFERND not reference itself, i.e., $Y_i = dY_i/dt$ not be allowed.

2. When the integral component is presented with

$$Y_i = \int_0^t Y_n \, dt \quad , \quad k > i$$

The advancement will be done by

$$Y_i^{n+1} = Y_i^n \left[\frac{1 + \frac{S\Delta t}{2}}{1 - \frac{S\Delta t}{2}} \right] \quad k = i$$

$$Y_i^{n+1} = SY_n^n \, \Delta t \qquad k > i \quad .$$

3. Units conversion be added for British units.

4. The input card numbering to be changed to allow a potential of 9999 components, and the actual limit of 999 be raised to 4095. Since this involves a change of existing decks, the default would be the old system and a separate card would specify the new numbering system. The number of trips should also be increased. Both of these expansions are in response to operator guideline requirements.

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