



**GEKKO**  
DYNAMIC OPTIMIZATION

## **GEKKO Documentation**

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# CHAPTER 1

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## Overview

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GEKKO is optimization software for mixed-integer and differential algebraic equations. It is coupled with large-scale solvers for linear, quadratic, nonlinear, and mixed integer programming (LP, QP, NLP, MILP, MINLP). Modes of operation include data reconciliation, real-time optimization, dynamic simulation, and nonlinear predictive control. GEKKO is an object-oriented python library to facilitate local execution of APMonitor.

More of the backend details are available at [What does GEKKO do?](#) and in the [GEKKO Journal Article](#). Example applications are available to [get started with GEKKO](#).



## CHAPTER 2

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### Installation

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A pip package is available:

```
pip install gekko
```

The most recent version is 0.1. You can upgrade from the command line with the upgrade flag:

```
pip install --upgrade gekko
```



## CHAPTER 3

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### Citing GEKKO

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If you use GEKKO in your work, please cite the following paper:

Beal, L.D.R., Hill, D., Martin, R.A., and Hedengren, J. D., GEKKO Optimization Suite, Processes, Volume 6, Number 8, 2018, doi: 10.3390/pr6080106.

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### 4.1 What does GEKKO do?

GEKKO is optimization software for mixed-integer and differential algebraic equations. It is coupled with large-scale solvers for linear, quadratic, nonlinear, and mixed integer programming (LP, QP, NLP, MILP, MINLP). Modes of operation include data reconciliation, real-time optimization, dynamic simulation, and nonlinear predictive control. The client or server is freely available with interfaces in MATLAB, Python, or from a web browser.

GEKKO is a high-level abstraction of mathematical optimization problems. Values in the models are defined by Constants, Parameters, and Variables. The values are related to each other by Intermediates or Equations. Objective functions are defined to maximize or minimize certain values. Objects are built-in collections of values (constants, parameters, and variables) and relationships (intermediates, equations, and objective functions). Objects can build upon other objects with object-oriented relationships.

The APMonitor executable on the back-end compiles a model to byte-code and performs model reduction based on analysis of the sparsity structure (incidence of variables in equations or objective function) of the model. For differential and algebraic equation systems, orthogonal collocation on finite elements is used to transcribe the problem into a purely algebraic system of equations. APMonitor has several modes of operation, adjustable with the imode parameter. The core of all modes is the nonlinear model. Each mode interacts with the nonlinear model to receive or provide information. The 9 modes of operation are:

1. Steady-state simulation (SS)
2. Model parameter update (MPU)
3. Real-time optimization (RTO)
4. Dynamic simulation (SIM)
5. Moving horizon estimation (EST)
6. Nonlinear control / dynamic optimization (CTL)
7. Sequential dynamic simulation (SQS)
8. Sequential dynamic estimation (SQE)
9. Sequential dynamic optimization (SQO)

Modes 1-3 are steady state modes with all derivatives set equal to zero. Modes 4-6 are dynamic modes where the differential equations define how the variables change with time. Modes 7-9 are the same as 4-6 except the solution is performed with a sequential versus a simultaneous approach. Each mode for simulation, estimation, and optimization has a steady state and dynamic option.

APMonitor provides the following to a Nonlinear Programming Solver (APOPT, BPOPT, IPOPT, MINOS, SNOPT) in sparse form:

- Variables with default values and constraints
- Objective function
- Equations
- Evaluation of equation residuals
- Sparsity structure
- Gradients (1st derivatives)
- Gradient of the equations
- Gradient of the objective function
- Hessian of the Lagrangian (2nd derivatives)
- 2nd Derivative of the equations
- 2nd Derivative of the objective function

Once the solution is complete, APMonitor writes the results in results.json that is loaded back into the python variables by GEKKO

When the system of equations does not converge, APMonitor produces a convergence report in 'infeasibilities.txt'. There are other levels of debugging that help expose the steps that APMonitor is taking to analyze or solve the problem. Setting *DIAGLEVEL* to higher levels (0-10) gives more output to the user. Setting *COLDSTART* to 2 decomposes the problem into irreducible sets of variables and equations to identify infeasible equations or properly initialize a model.

## 4.2 Quick Start Model Building

### 4.2.1 Model

Create a python model object:

```
from gekko import GEKKO
m = GEKKO([server], [name]):
```

### 4.2.2 Variable Types

GEKKO has eight types of variables, four of which have extra properties.

Constants, Parameters, Variables and Intermediates are the standard types. Constants and Parameters are fixed by the user, while Variables and Intermediates are degrees of freedom and are changed by the solver. All variable declarations return references to a new object.

Fixed Variables (FV), Manipulated Variables (MV), State Variables (SV) and Controlled Variables (CV) expand parameters and variables with extra attributes and features to facilitate dynamic optimization problem formulation and robustness for online use. These attributes are discussed in *Manipulated Variable Options* and *Controlled Variable Options*.

All of these variable types have the optional argument 'name'. The name is used on the back-end to write the model file and is only useful if the user intends to manually use the model file later. Names are case-insensitive, must begin with a letter, and can only contain alphanumeric characters and underscores. If a name is not provided, one is automatically assigned a unique letter/number (c#/p#/v#/i#).

## Constants

Define a Constant. There is no functional difference between using a GEKKO Constant, a python variable or a magic number in the Equations. However, the Constant can be provided a name to make the .apm model more clear:

```
c = m.Const(value, [name]):
```

- Value must be provided and must be a scalar

## Parameters

Parameters are capable of becoming MVs and FVs. Since GEKKO defines MVs and FVs directly, parameters just serve as constant values. However, Parameters (unlike Constants) can be (and usually are) arrays.:

```
p = m.Param([value], [name])
```

- The value can be a python scalar, python list of numpy array. If the value is a scalar, it will be used throughout the horizon.

## Variable

Calculated by solver to meet constraints (Equations):

```
v = m.Var([value], [lb], [ub], [integer], [name]):
```

- *lb* and *ub* provide lower and upper variable bounds, respectively, to the solver.
- *integer* is a boolean that specifies an integer variable for mixed-integer solvers

## Intermediates

Intermediates are a unique GEKKO variable type. Intermediates, and their associated equations, are like variables except their values and gradients are evaluated explicitly, rather than being solved implicitly by the optimizer. Intermediate variables essentially blend the benefits of sequential solver approaches into simultaneous methods.

The function creates an intermediate variable *i* and sets it equal to argument *equation*:

```
i = m.Intermediate(equation, [name])
```

*Equation* must be an explicitly equality. Each intermediate equation is solved in order of declaration. All variable values used in the explicit equation come from either the previous iteration or an intermediate variable declared previously.

## Fixed Variable

Fixed Variables (FV) inherit Parameters, but potentially add a degree of freedom and are always fixed throughout the horizon (i.e. they are not discretized in dynamic modes):

```
f = m.FV([value], [lb], [ub], [integer], [name])
```

- *lb* and *ub* provide lower and upper variable bounds, respectively, to the solver.
- *integer* is a boolean that specifies an integer variable for mixed-integer solvers

### Manipulated Variable

Manipulated Variables (MV) inherit FVs but are discretized throughout the horizon and have time-dependent attributes:

```
m = m.MV([value], [lb], [ub], [integer], [name])
```

- *lb* and *ub* provide lower and upper variable bounds, respectively, to the solver.
- *integer* is a boolean that specifies an integer variable for mixed-integer solvers

### State Variable

State Variables (SV) inherit Variables with just a couple extra attributes:

```
s = m.SV([value], [lb], [ub], [integer], [name])
```

### Controlled Variable

Controlled Variables (CV) inherit SVs but potentially add an objective (such as reaching a setpoint in control applications or matching model and measured values in estimation):

```
c = m.CV([value], [lb], [ub], [integer], [name])
```

## 4.2.3 Equations

Equations are defined with the variables defined and python syntax:

```
m.Equation(equation)
```

For example, with variables *x*, *y* and *z*:

```
m.Equation(3*x == (y**2)/z)
```

**Multiple equations can be defined at once if provided in an array or python list::** `m.Equations(eqs)`

Equations are all solved implicitly together.

## 4.2.4 Objectives

Objectives are defined like equations, except they must not be equality or inequality expressions. Objectives are always minimized (maximization is possible by multiplying the objective by -1):

```
m.Obj(obj)
```

## 4.2.5 Example

Here's an example script for solving problem HS71

```

from gekko import GEKKO

#Initialize Model
m = GEKKO()

#define parameter
eq = m.Param(value=40)

#initialize variables
x1,x2,x3,x4 = [m.Var(lb=1, ub=5) for i in range(4)]

#initial values
x1.value = 1
x2.value = 5
x3.value = 5
x4.value = 1

#Equations
m.Equation(x1*x2*x3*x4>=25)
m.Equation(x1**2+x2**2+x3**2+x4**2==eq)

#Objective
m.Obj(x1*x4*(x1+x2+x3)+x3)

#Set global options
m.options.IMODE = 3 #steady state optimization

#Solve simulation
m.solve()

#Results
print('')
print('Results')
print('x1: ' + str(x1.value))
print('x2: ' + str(x2.value))
print('x3: ' + str(x3.value))
print('x4: ' + str(x4.value))

```

## 4.2.6 Connections

Connections are processed after the parameters and variables are parsed, but before the initialization of the values. Connections are the merging of two variables or connecting specific nodes of a discretized variable. Once the variable is connected to another, the variable is only listed as an alias. Any other references to the connected value are referred to the principal variable (*var1*). The alias variable (*var2*) can be referenced in other parts of the model, but will not appear in the solution files.

```
m.Connection(var1, var2, pos1=None, pos2=None, node1='end', node2='end')
```

*var1* must be a GEKKO variable, but *var2* can be a static value. If *pos1* or *pos2* is not *None*, the associated var must be a GEKKO variable and the position is the (0-indexed) time-discretized index of the variable.

## 4.3 Modes

### 4.3.1 IMODE

`model.options.IMODE` defines the problem type. Each problem type treats variable classes differently and builds equations behind the scenes to meet the particular objective inherit to each problem type. The modes are:

	Simulation	Estimation	Control
Non-Dynamic	1 Sys of Eq	2 MPU	3 RTO
Dynamic Simultaneous	4 ODE Solver	5 MHE	6 MPC
Dynamic Sequential	7 ODE Solver	8 MHE	9 MPC

### 4.3.2 Dynamics

Ordinary differential equations are specified by differentiation a variable with the `dt()` method. For example, velocity  $v$  is the derivative of position  $x$ :

```
m.Equation( v == x.dt() )
```

Discretization is determined by the model `time` attribute. For example, `m.time = [0,1,2,3]` will discretize all equations and variable at the 4 points specified. Only ordinary differential equations discretized by time are available internally. Other discretization must be performed manually.

Simultaneous methods use orthogonal collocation on finite elements to implicitly solve the DAE system. Non-simulation simultaneous methods (modes 5 and 6) simultaneously optimize the objective and implicitly calculate the model/constraints. Simultaneous methods tend to perform better for problems with many degrees of freedom.

Sequential methods separate the NLP optimizer and the DAE simulator. Sequential methods will satisfy the differential equations, even when the solver is unable to find a feasible optimal solution.

Non-Dynamic modes sets all differential terms to zero to calculate steady-state conditions.

### 4.3.3 Simulation

Simulation just solves the given equations. These modes provide little benefit over other equation solver or ODE integrator packages. However, successful simulation of a model within GEKKO helps debug the model and greatly facilitates the transition from model development/simulation to optimization.

### 4.3.4 Estimation

#### MPU

Model Parameter Update is parameter estimation for non-dynamic conditions. .. This mode implements the special variable types as follows:

#### MHE

Moving Horizon Estimation is for dynamic estimation, both for states and parameter regression. The horizon to match is the discretized time horizon of the model `m.time`. `m.time` should be discretized at regular intervals. New measurements are added at the end of the horizon (e.g. `m.time[-1]`) and the oldest measurements (e.g. `m.time[0]`) are dropped off.

timeshift enables automatic shifting of all variables and parameters with each new solve of a model. The frequency of new measurements should match the discretization of *m.time*.

## FV

Fixed variables are fixed through the horizon.

*STATUS* adds one degree of freedom for the optimizer, i.e. a fixed parameter for fit.

*FSTATUS* allows giving a fixed measurement.

## MV

Manipulated variables are like FVs, but discretized with time.

*STATUS* adds one degree of freedom for each time point for the optimizer, i.e. a dynamic parameter for fit.

*FSTATUS* allows giving a measurements for each time.

## CV

Controlled variables are the measurement to match.

If *FSTATUS* is on (*FSTATUS=1*), an objective function is added to minimize the model prediction to the measurements. The error is either squared or absolute depending on if *m.options.EV\_TYPE* is 2 or 1, respectively. *FSTATUS* enables receiving measurements through the *MEAS* attribute.

If *m.options.EV\_TYPE = 1*, *CV.MEAS\_GAP=v* will provide a dead-band of size *v* around the measurement to avoid fitting to measurement noise.

*STATUS* is ignored in MHE.

## 4.3.5 Control

### RTO

Real-Time Optimization

### MPC

Model Predictive Control

Controlled variables are the objective to match. When *STATUS=1* for a CV, the objective includes a minimization between model predictions and the setpoint.

If *m.options.CV\_TYPE=1*, the objective is an l1-norm (absolute error) with a dead-band. The setpoint range should be specified with *SPHI* and *SPLO*. If *m.options.CV\_TYPE=2*, the objective is an l2-norm (squared error). The setpoint should be specified with *SP*.

The other setpoint options include *TAU*, *TIER*, *TR\_INIT*, *TR\_OPEN*, *WSP*, *WSPHI*, and *WSPLO*.

## 4.4 Global Options

The following is a list of global model attributes. Each attribute is available through the model attributes *options*, eg:

```
from gekko import GEKKO
m = GEKKO()
m.options.IMODE = 3
```

GEKKO only allows input options to be written, while all options can be read.

This is a complete list of the configuration parameters. Each section includes an indication of the variable type (Integer or Real), the default value, data flow, and description.

### 4.4.1 APPINFO

Type: Integer, Output

Default Value: 0

Description: Application information: 0=good, error otherwise

Explanation: APPINFO is an error code when the solution is not successful. The meaning of an error code is different for each solver that is selected. The one common code is a value of 0 that always indicates a successful solution. APPINFO is a more detailed error report than APPSTATUS that only gives a binary indication of application success.

### 4.4.2 APPINFOCHG

Type: Integer, Output

Default Value: 0

Description: Application information change (new-old): 0=no change

Explanation: APPINFOCHG is the difference between the prior value of APPINFO and the most current value of APPINFO. The difference is useful in determining when an application solution may have changed due to several factors as reported by the error code when APPINFOCHG is non-zero.

### 4.4.3 APPSTATUS

Type: Integer, Output

Default Value: 1

Description: Application status: 1=good, 0=bad

Explanation: APPSTATUS is the overall health monitoring for an application. An application may be unsuccessful for a number of reasons and the APPSTATUS changes to 0 (bad) if it is not able to provide a solution. The APPSTATUS is 1 (good) when the solver converges to a successful solution and there are no errors in reporting the solution.

### 4.4.4 AUTO\_COLD

Type: Integer, Input

Default Value: 0

Description: Automatically cold start model after a specified number of bad cycles 0 = do not auto coldstart 1+ = cold start after specified number of bad cycles as recorded by BAD\_CYCLES

Explanation: AUTO\_COLD is the number of consecutive bad cycles to wait to attempt a COLDSTART as an initialization mode for an application. It is by default at 0 (no action with bad cycles) but can be set to a higher integer level (1+) as a trigger to initiate a coldstart. When the AUTO\_COLD limit is reached, the COLDSTART flag is set to 1 (ON) and it remains on until there is a successful solution. Once a successful solution is found, COLDSTART and BAD\_CYCLES are set to zero.

#### 4.4.5 BAD\_CYCLES

Type: Integer, Input/Output

Default Value: 0

Description: Counter on number of bad cycles 0 = initial value 1+ = number of consecutive unsuccessful solution attempts

Explanation: BAD\_CYCLES is a counter that increments when the application fails to produce a successful solution. When BAD\_CYCLES reaches the AUTO\_COLD limit, a COLDSTART is initiated. Once a successful solution is found, COLDSTART and BAD\_CYCLES are set to zero.

#### 4.4.6 BNDS\_CHK

Type: Integer, Input

Default Value: 1

Description: Bounds checking: 1=ON, 0=OFF

Explanation: BNDS\_CHK validates a measurement with VLHI, VLLO, and VDVL properties. When BNDS\_CHK is OFF, there is no checking of the validity limits. Although an application may have specific validity limits set, it is occasionally desirable to take off the checks to observe raw data input to the model without error detection. All measurement validation actions are reported in the text file `dbb_read.rpt`. BNDS\_CHK, FRZE\_CHK, and MEAS\_CHK are options regarding data cleansing before it enters the applications. When a measurement is bad, the LSTVAL is restored as the measured value or else LSTVAL+VDVL or LSTVAL-VDVL. The VDVL shift depends on whether VLACTION is 0 (keep LSTVAL) or else is 1 (step by VDVL towards measurement).

#### 4.4.7 COLDSTART

Type: Integer, Input/Output

Default Value: 0

Description: Cold start model: 0=warm start, 1=cold start, 2=decompose problem

Explanation: COLDSTART is an initialization mode for an application. It is by default at 0 (no initialization) but can be set to higher levels (1 or 2) to handle cases where initialization of the problem is a key enabler for a successful solution or to reset an application after a failed solution or a period of inactivity. The initialization values are typically taken from a prior solution as stored in `t0` files on the server. When COLDSTART $\geq$ 1, the `t0` files are ignored and the initialization values are taken from the file, the DBS file, and the CSV file in that order. A value of 1 indicates that all FV, MV, and CV STATUS values are turned off (0) temporarily to reduce the number of degrees of freedom and achieve a feasible, yet suboptimal solution. A value of 2 is a more aggressive initialization where the degrees of freedom are turned off and the sparsity of the problem is analyzed to create a sequence of lower block triangular segments. These segments are solved sequentially and an error is reported if a particular block is infeasible. Therefore, COLDSTART=2 is one method to help identify equations or variables bounds that may be causing an infeasible solution. Once the

application is successfully solved with  $COLDSTART \geq 1$ , the value of  $COLDSTART$  is automatically reset to 0 for the next solution.

#### 4.4.8 CSV\_READ

Type: Integer, Input

Default Value: 2

Description: CSV read: 0=Off, 1=Batch, 2=Sequential

Explanation:  $CSV\_READ$  indicates whether a comma separated value data file should be used by the application as part of initializing a problem and loading data. The name of the CSV file is the same as the name of the model file.

Values assigned to GEKKO variables and the model time are primarily communicated to APMonitor through the csv file. If  $CSV\_READ=0$ , only scalar values of parameters and variables are read through the .apm file. If  $CSV\_READ=1$ , all parameter values are also read in. If  $CSV\_READ=2$ , all parameter and (initial) variable values are loaded.

Only values defined by the user since model initialization or the last solve are written to the csv. All other values are loaded back from the APM internal .t0 database files and timeshifted according to the  $TIME\_SHIFT$  option. If a measurement (.MEAS) is defined, the associated variable value is not written to the csv. Also, if a variable value is fixed with the  $fix()$  command, the fixed value is written in the csv file.

#### 4.4.9 CSV\_WRITE

Type: Integer, Input

Default Value: 0

Description: CSV write: 0=Off, 1=Write results.csv, 2=Write results\_all.csv

Explanation:  $CSV\_WRITE$  is an option that controls how much information is written to results files. When it is 0 (OFF), no result files are written. This may be desirable to further reduce the time associated with solution post-processing. When  $CSV\_WRITE=1$ , a file results.csv is written with all of the constants, parameters, and variables. The data is written in a row oriented form with each row header as the name and subsequent column values are the values at each of the time points requested in the input data file. The values from results.csv are automatically loaded back to the GEKKO variables' attribute *value*. When  $CSV\_WRITE=2$ , another file named results\_all.csv is produced that contains not only the endpoints but also the intermediate collocation nodes of the solution. This data file is saved in the model path, visible by  $print(m\_path)$ .

#### 4.4.10 CTRLMODE

Type: Integer, Output

Default Value: 1

Description: Control mode: 0=terminate, 1=simulate, 2=predict, 3=control

Explanation: The  $CTRLMODE$  is the actual controller mode implemented by the application and is an output after the application has completed each cycle. The requested control mode ( $REQCTRLMODE$ ) is set as an input to the desired level of control but sometimes the  $CTRLMODE$  is not able to match the request because of a failed solution, a critical MV is OFF, or other checks with the application. A  $CTRLMODE$  level of 0 indicates that the program did not run due to a request to terminate. A  $CTRLMODE$  level of 1 (cold mode) indicates that the program was run as a simulator with all STATUS values turned off on FVs, MVs, and CVs. A  $CTRLMODE$  level of 2 (warm mode) indicates that the application calculates control actions but only after the second cycle. This mode is commonly used to observe anticipated control actions before the controller is activated to level 3. The  $CTRLMODE$  level of 3 means that the controller is ON and implementing changes to the process.

#### 4.4.11 CTRL\_HOR

Type: Integer, Input or Output (with CSV read)

Default Value: 1

Description: Control horizon: Horizon length where MVs can be adjusted by the solver

Explanation: CTRL\_HOR is the control horizon in the beginning portion of the time horizon where MV changes are allowed. There is also a PRED\_HOR (prediction horizon) that is greater than or equal to CTRL\_HOR. As opposed to CTRL\_HOR, no manipulated variable movement is allowed in the prediction horizon. The individual size of time steps of the control horizon are set with CTRL\_TIME. The individual size of time steps of the prediction horizon are set with PRED\_TIME. The PRED\_TIME is generally larger than the CTRL\_TIME to give a section of the overall horizon that predicts steady state arrival to the set point. When CSV\_READ is on and the horizon time points are specified from the data file, the CTRL\_HOR and PRED\_HOR are set equal to the number of time steps present in the data file.

#### 4.4.12 CTRL\_TIME

Type: Real, Input or Output (with CSV read)

Default Value: 60

Description: Time for each step in the control horizon

Explanation: CTRL\_TIME is the cycle time of the controller for real-time applications. The clock time trigger for initiating successive controller solutions should be synchronized with CTRL\_TIME to avoid dynamic mismatch between the internal simulation time and the process measurements. When CSV\_READ is on and the horizon time points are specified from the data file, the CTRL\_TIME and PRED\_TIME are set equal to the time increment of the first time step.

#### 4.4.13 CTRL\_UNITS

Type: Integer, Input

Default Value: 1

Description: Model time units (1=sec, 2=min, 3=hrs, 4=days, 5=yrs)

Explanation: CTRL\_UNITS are the time units of the model. This option does not affect the solution but does affect the x-axis of the web plots. The time displayed on the web plots is shown according to the HIST\_UNITS option but scaled from the model units as specified by CTRL\_UNITS. The valid options are 1=sec, 2=min, 3=hrs, 4=days, and 5=yrs. If CTRL\_UNITS=1 and HIST\_UNITS=2 then the model is in seconds and the web plots have model predictions and measurements that are displayed in minutes.

#### 4.4.14 CV\_TYPE

Type: Integer, Input

Default Value: 1

Description: Controlled variable error model type: 1=linear, 2=squared, 3=ref traj

Explanation: CV\_TYPE is a selection of the type of objective function to be used for variables defines as controlled variables (CVs) in control (IMODE=6 or 9) applications. The options are to use a linear penalty from a dead-band trajectory (CV\_TYPE=1), squared error from a reference trajectory (CV\_TYPE=2), or an experimental reference trajectory type (CV\_TYPE=3).

#### 4.4.15 CV\_WGT\_SLOPE

Type: Real, Input

Default Value: 0.0

Description: Slope for weight on future CV error (e.g. [+] favors steady state)

Explanation: CV\_WGT\_SLOPE is how the controlled variable WSPHI, WSPLO, or WSP change with time over the control horizon. This option is used to favor either near-term attainment of the setpoint or long-term (future) steady state tracking. It is normally set to zero but can be adjusted to be positive to increase the weighting for future time points or negative to decrease the weighting for future time points.

#### 4.4.16 CV\_WGT\_START

Type: Integer, Input

Default Value: 0

Description: Start interval for controlled variable error model weights

Explanation: CV\_WGT\_START is the time step that the controlled variables WSPHI, WSPLO, or WSP start. Before this time step, there is no penalty so that there are no near term objectives to reach a setpoint or trajectory. This option is used to consider long-term (future) steady state tracking while ignoring the near-term path to achieve the final target. It is normally set to zero but can be adjusted to be any positive integer between 0 and the number of time steps in the horizon.

#### 4.4.17 CYCLECOUNT

Type: Integer, Input with Output (+1)

Default Value: 0

Description: Cycle count, increments every cycle

Explanation: CYCLECOUNT is a counter that records the number of cycles of the application. It is both an input and output value because the CYCLECOUNT value can be reset. The CYCLECOUNT may be reset when it is desirable to record when a certain event occurs such as a set point change or when the application is re-initialized.

#### 4.4.18 DBS\_LEVEL

Type: Integer, Input

Default Value: 1

Description: Database level limited to a subset of options 0=Basic, Limited Options 1=All Options

Explanation: DBS\_LEVEL is an input option to control what is written to the DBS (database) file. When DBS\_LEVEL=0, only a subset of basic parameters are written to the DBS file. This is used for compatibility with some industrial control systems that only support a subset of parameters. The basic global parameters are the following:

APPINFO, APPINFOCHG, APPSTATUS, COLDSTART, CYCLECOUNT, DIAGLEVEL, ITERATIONS, OBJFCNVAL, REQCTRLMODE, SOLVESTATUS, SOLVETIME

Local parameters that are designated as basic types are only used when DBS\_LEVEL=0:

BIAS, COST, CRITICAL, DCOST, DMAX, DMAXHI, DMAXLO, FSTATUS, LOWER, LSTVAL, MEAS, MODEL, NEWVAL, NXTVAL, PSTATUS, REQONCTRL, SP, SPHI, SPLO, STATUS, TAU, UPPER, VDV, VLHI, VLLO, WSPHI, WSPLO

#### 4.4.19 DBS\_READ

Type: Integer, Input

Default Value: 1

Description: Database read: 0=OFF, 1={Name = Value, Status, Units}, 2={Name,Value}

Explanation: DBS\_READ specifies when to read the input DBS files with 0=OFF, 1=Read values with Units, and 2=Read values without Units. There are several text file database (DBS) files that are read at the start of an application for both configuring the problem as well as reading in measurements. The DBS files are skipped when DBS\_READ=0 except for header parameters. The DBS files are read in the order of defaults.dbs, {problem name}.dbs, measurements.dbs (source is replay.csv when REPLAY>=1), and overrides.dbs. The DBS files may be need to be skipped to re-initialize an application without feedback from the process.

#### 4.4.20 DBS\_WRITE

Type: Integer, Input

Default Value: 1

Description: Database write: 0=OFF, 1={Name = Value, Status, Units}, 2={Name,Value}

Explanation: DBS\_WRITE specifies when to write the output DBS files with 0=OFF, 1=Write values with Units, and 2=Write values without Units. It may be desirable to turn off the DBS file writing when the DBS file sends feedback to the process and the application is under development.

#### 4.4.21 DIAGLEVEL

Type: Integer, Input

Default Value: 0

Description: Diagnostic level: 0=none, 1=messages, 2=file checkpoints, 4=diagnostic files, 5=check 1st deriv

Explanation: DIAGLEVEL is the diagnostic level for an application. With higher levels, it is used to give increasingly greater detail about the model compilation, validation, and traceability of information. At level 0, there is minimal information reported that typically includes a summary of the problem and the solver output. At level 1, there are more information messages and timing information for the different parts of the program execution. At level 2, there are diagnostic files created at every major step of the program execution. A diagnostic level of >=2 slows down the application because of increased file input and output, validation steps, and reports on problem structure. Additional diagnostic files are created at level 4. The analytic 1st derivatives are verified with finite differences at level 5 and analytic 2nd derivatives are verified with finite differences at level 6. The DIAGLEVEL is also sent to the solver to indicate a desire for more verbose output as the level is increased. Some solvers do not support increased output as the diagnostic level is increased. A diagnostic level up to 10 is allowed.

#### 4.4.22 EV\_TYPE

Type: Integer, Input

Default Value: 1

Description: Estimated variable error model type: 1=linear, 2=squared, 3=approximate linear

Explanation: EV\_TYPE applies a specific objective function. Linear is an l1-norm, or in other words the solver minimizes the sum of the absolute value of the difference between the CV and the set point. Squared is an l2-norm or sum squared error (SSE), or in other words the solver minimizes the sum of the squared difference between the CV

and the set point. 11-norm can be useful when noise or measurement error is expected because it better rejects those. Option 3 is not typically used as an approximate absolute value function that uses a nonlinear function instead of slack variables.

#### **4.4.23 EV\_WGT\_SLOPE**

Type: Real, Input

Default Value: 0.0

Description: Slope for weight on more current EV error (e.g. favor near-term matching)

Explanation: EV\_WGT\_SLOPE is how the weight on measurement error (WMEAS) and prior model difference (WMODEL) change with time over the estimation horizon. This option is typically used to favor alignment of the most recent data. It is normally set to zero but can be adjusted to be positive to increase the weighting for more recent data points.

#### **4.4.24 FILTER**

Type: Floating Point, Input

Default Value: 1.0

Description: Measurement first-order filter: (0-1)

Explanation: FILTER determines how much of the raw measurement is used to update the value of MEAS. A filter of 0 indicates that the measurement should not be used in updating the MEAS value. The FILTER parameter applies to all inputs into the model from the CSV (data) file and also from the DBS (database) file. FILTER at 1.0 uses all of the measurement and ignores any prior measurement value and 0.5 uses half of each.

CSV (data) file

Model = Model \* (1-FILTER) + Measured \* FILTER

DBS (database) file

MEAS = MEAS \* FILTER + LSTVAL \* (1-FILTER)

The FSTATUS parameter is used to adjust the fractional update from new measurements, but this only applies to a single entity at a time. FILTER applies globally to all inputs. Both FSTATUS and FILTER are useful to control the flow of information into the model. It is sometimes desirable to set FILTER or FSTATUS to a low value (close to 0) when the solver is not able to find a solution because of big input changes. A drawback of a filter on data is that raw inputs are not used in the application and it takes several cycles to reach true input values.

#### **4.4.25 FRZE\_CHK**

Type: Integer, Input

Default Value: 1

Description: Frozen measurement checking 1=ON 0=OFF

Explanation: FRZE\_CHK is a checking mechanism to ensure that a measurement has variation and is not frozen at the same value for repeat cycles of the application. If the measurement does not change, it is marked as bad and not used in the application. FRZE\_CHK is useful for certain types of measurements that are known to periodically fail and stay at a constant value, such as gas chromatographs. FRZE\_CHK can also detect when the application is cycling at a faster rate than the measurement device can deliver a new measurement. FRZE\_CHK may be undesirable if the sensor resolution gives a false indication of a frozen measurement when it is actually a steady signal and poor

sensor resolution. When FRZE\_CHK is OFF, there is no checking of the difference from the prior measurement. BNDS\_CHK, FRZE\_CHK, and MEAS\_CHK are options regarding data cleansing before it enters the applications.

#### 4.4.26 HIST\_HOR

Type: Integer, Input

Default Value: 0

Description: History horizon in web plot displays: Integer  $\geq 0$

Explanation: HIST\_HOR is the number of historical data points to display in the web browser plots. The history horizon values are appended to hst files stored on the server. When HIST\_HOR is very large, it can slow down the rendering of the plots or expand the display horizon so much that it can be difficult to distinguish near-term movement. The HIST\_HOR does not affect the solution, only the display of prior results. The history always trails off the back of the horizon for simulation, estimation, or control modes. For simulation and control, the newest history points are the initial conditions from the prior cycle. For estimation, the newest history points are also from the initial conditions. Initial conditions from estimation problems are not the current time but from the earliest part of the moving horizon that is time shifted off of the estimation horizon.

#### 4.4.27 HIST\_UNITS

Type: Integer, Input

Default Value: 0

Description: History time units on plots only (0=same as CTRL\_UNITS, 1=sec, 2=min, 3=hrs, 4=days, 5=yrs)

Explanation: HIST\_UNITS are the plots displayed in the web browser. This option does not affect the solution but does affect the x-axis of the web plots. The time displayed on the web plots is shown according to the HIST\_UNITS option but scaled from the model units as specified by CTRL\_UNITS. The valid options are 1=sec, 2=min, 3=hrs, 4=days, and 5=yrs. If CTRL\_UNITS=1 and HIST\_UNITS=2 then the model is in seconds and the web plots have model predictions and measurements that are displayed in minutes.

#### 4.4.28 ICD\_CALC

Type: Integer, Input

Default Value: 0

Description: Specifications for initial condition differentials (MHE only): 0=OFF, 1=ON

Explanation: ICD\_CALC is an option for the initial conditions that are associated with differential variables in estimation applications (IMODE=5 or 8). When ICD\_CALC=1 (ON), the algebraic variables remain fixed at current values but the differential variables become adjustable by the solver. Any value in the time horizon can be fixed or calculated by setting FIXED or CALCULATED in a CONNECTIONS section of the model. The ICD\_CALC option is typically used when estimation problems have uncertain initial conditions, especially during initialization. Leaving ICD\_CALC=1 (ON), may reduce the predictive capability of a model to check for conservation of mass or energy because the differential equations are not enforced for the initial conditions.

#### 4.4.29 IMODE

Type: Integer, Input

Default Value: 3

Description: Model solution mode: 1=ss, 2=mpu, 3=rto, 4=sim, 5=est, 6=ctl

Explanation: IMODE sets the mode or type of model solution. IMODE=1-3 uses steady state models, meaning that all differential variables are set to zero and there are no model dynamics. Options 4-9 calculate the dynamics with either simulation, estimation, or control. There are three modes each for steady state (IMODE=1-3), simultaneous method to compute the dynamics (IMODE=4-6), and sequential method to compute the dynamics (IMODE=7-9). The first option in each set is simulation (IMODE=1, 4, and 7) where the problem must have the same number of variables and equations and optimization is not allowed. The second option in each set is estimation where model parameters such as FVs and MVs or initial conditions are adjusted to match measured values (IMODE=2, 5, and 8). The third option in each set is optimization or control where controlled variables are driven to a desired target value or an objective function is either maximized or minimized (IMODE=3, 6, 9).

### 4.4.30 ITERATIONS

Type: Integer, Output

Default Value: 1

Description: Iterations for solution:  $\geq 1$

Explanation: ITERATIONS are the number of major iterations required to find a solution. If the number of iterations reaches MAX\_ITER, the unfinished solution is returned with an error message. The number of iterations is typically in the range of 3-100 for most problems although this number can be higher for large-scale or complex systems.

### 4.4.31 LINEAR

Type: Integer, Input

Default Value: 0

Description: 0 - Nonlinear problem 1 - Linear problem

Explanation: Linear programming (LP) or mixed integer linear programming (MILP) problems can typically be solved much faster than a comparably sized nonlinear programming problem. The LINEAR option indicates whether the problem is linear. This allows the modeling language to set options in certain nonlinear solvers that improve the efficiency of the solution. All of the solvers built into APMonitor are nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP) solvers. Some of the solvers have simplifications to handle linear problems as well. This option does not override the choice of solver with SOLVER but does communicate to the solver that the problem has linear structure.

### 4.4.32 MAX\_ITER

Type: Integer, Input

Default Value: 100

Description: Maximum iteration:  $\geq 1$

Explanation: MAX\_ITER is the maximum number of major iterations for solution by the solver. If this number is reached, the result cannot be trusted because the equation convergence or objective minimization does not satisfy the Karush Kuhn Tucker conditions for optimality. Reaching the maximum number of iterations can happen when the problem is large, difficult, highly nonlinear or if the problem is infeasible. Increasing MAX\_ITER for infeasible problems will not lead to a feasible solution but can help detect the infeasible conditions.

### 4.4.33 MAX\_MEMORY

Type: Integer, Input

Default Value: 4

Description: Maximum memory utilized during model compilation with range  $10^2$  to  $10^{10}$

Explanation: Computer memory is allocated at run-time based on the size of the problem but there are particular parts during the model compilation that need an upper limit on model complexity. `MAX_MEMORY=4` allows up to  $10^4 = 10,000$  sparsity elements per equation but can go up to  $10^{10}$ . There are rare cases when more sparsity elements are needed than the default of 10,000. In these cases, an error message states that the amount of memory should be increased with the option `MAX_MEMORY`. A good practice is to increase `MAX_MEMORY` by an order of magnitude (+1) until the error is not encountered. Increasing `MAX_MEMORY` requires more Random Access Memory (RAM) when the model is compiled at the start of each optimization problem.

### 4.4.34 MAX\_TIME

Type: Real, Input

Default Value: 1.0e20

Description: Maximum run time in seconds

Explanation: `MAX_TIME` is the maximum amount of clock time in seconds that the solver should continue. Solutions forced to terminate early by this constraint do not satisfy the Karush Kuhn Tucker conditions for optimality. Even with this constraint, the application may fail to terminate at the required time because there are limited checks within the solvers. If a solver is stuck in a single major iteration when the time limit is reached, the program will terminate once that major iteration is completed. A supervisory application at the operating system level should generally be used to terminate applications that exceed a maximum desired amount of clock or CPU time.

### 4.4.35 MEAS\_CHK

Type: Integer, Input

Default Value: 1

Description: Measurement checking: 1=ON, 0=OFF

Explanation: `MEAS_CHK` indicates whether to check the validity of measurements before they are used in an application. When `MEAS_CHK=0` (OFF), there is no checking of the measurement. Although an application may have specific validation limits, it is occasionally desirable to take off the checks to observe raw data input to the model without error detection. All measurement validation actions are reported in the text file `dbb_read.rpt`. `BNDS_CHK`, `FRZE_CHK`, and `MEAS_CHK` are options regarding data cleansing before it enters the applications. When a measurement is bad, the `LSTVAL` is restored as the measured value or else `LSTVAL+VDVL` or `LSTVAL-VDVL`. The `VDVL` shift depends on whether `VLACTION` is 0 (keep `LSTVAL`) or else is 1 (step by `VDVL` towards measurement).

### 4.4.36 MV\_D COST\_SLOPE

Type: Real, Input

Default Value: 0.1

Description: Slope for penalization on future MV moves (i.e. reduces controller procrastination)

Explanation: `MV_D COST_SLOPE` implements a linear increase in movement penalty (DCOST). The increase in DCOST favors near term movement in the manipulated variable. One issue with a deadband trajectory is a phenomena

called controller procrastination where the optimal solution delays a move because it gives an equal objective function to wait one or more cycles. This causes the controller to be stuck in a state of inaction. Favoring movement on the first step of the controller avoids this delay in implementing the needed changes.

#### 4.4.37 MV\_STEP\_HOR

Type: Integer, Input

Default Value: 1 (for MV\_STEP\_HOR) or 0 (for MV(#).MV\_STEP\_HOR)

Description: Step length for manipulated variables: 0 uses MV\_STEP\_HOR as default

Explanation: MV\_STEP\_HOR is the horizon length between each allowable movement of the manipulated variables. There are cases where the MV should not move every time step but should be constrained to move only a certain multiple of the collocation time step. With MV\_STEP\_HOR = 2, the manipulated variable is allowed to move on the first step and every other step thereafter. MV\_STEP\_HOR = 5, the manipulated variable is allowed to move on the first step and every 5th step thereafter. There is also a parameter MV\_STEP\_HOR that is used as a global configuration for all MVs when the individual MV option is set to 0.

#### 4.4.38 MV\_TYPE

Type: Integer, Input

Default Value: 0

Description: Manipulated variable type: 0=zero order hold, 1=linear

Explanation: MV\_TYPE specifies either a zero order hold (0) or a first order linear (1) interpolation between the MV endpoints. When the MV\_STEP\_HOR is two or greater, the MV\_TYPE is applied only to each segment where adjustments are allowed. The MV segment is otherwise equal to the prior time segment. The MV\_TYPE only influences the solution when the number of NODES is between 3 and 6. It is not important when NODES=2 because there are no interpolation nodes between the endpoints.

#### 4.4.39 NODES

Type: Integer, Input

Default Value: 3

Description: Nodes in each horizon step

Explanation: NODES are the number of collocation points in the span of each time segment. For dynamic problems, the time segments are linked together into a time horizon. Successive endpoints of the time segments are merged to form a chain of model predictions. Increasing the number of nodes will generally improve the solution accuracy but also increase the problem size and computation time. Solution accuracy can also be improved by adding more time segments.

#### 4.4.40 OBJFCNVAL

Type: Real, Output

Default Value: 0.0

Description: Objective function value

Explanation: OBJFCNVAL is the objective function value reported by the solver. All objectives are converted to a minimization form before solution is attempted. Any maximization terms are multiplied by -1 to convert to an

equivalent minimization form. For maximization problems, the objective function should be multiplied by -1 after retrieving OBJFCNVAL. The objective function may include multiple terms, not just a single objective. OBJFCNVAL is a summation of all objectives.

#### 4.4.41 OTOL

Type: Real, Input

Default Value: 1.0e-6

Description: Objective function tolerance for successful solution

Explanation: OTOL is the relative objective function tolerance for reporting a successful solution. A lower value of OTOL, such as 1e-8, will give a more precise answer but at the expense of more iterations. The default of 1e-6 is generally sufficient for most problems. However, there are times when there are multiple objectives and higher precision is required to fully resolve minor objectives. OTOL and RTOL (relative tolerance on the equations) should generally be adjusted together.

#### 4.4.42 PRED\_HOR

Type: Integer, Input or Output (with CSV read)

Default Value: 1.0

Description: Prediction horizon: Total horizon, including control horizon

Explanation: PRED\_HOR is the prediction horizon that includes the control horizon and any additional points to track towards steady state. The PRED\_HOR must be greater than or equal to CTRL\_HOR (control horizon). As opposed to CTRL\_HOR, no manipulated variable movement is allowed in the prediction horizon. The individual size of time steps of the prediction horizon beyond the control horizon are set with PRED\_TIME. The PRED\_TIME is generally larger than the CTRL\_TIME to give a section of the overall horizon that predicts steady state arrival to the set point. When CSV\_READ is on and the horizon time points are specified from the data file, the CTRL\_HOR and PRED\_HOR are set equal to the number of time steps present in the data file.

#### 4.4.43 PRED\_TIME

Type: Real, Input or Output (with CSV read)

Default Value: 60.0

Description: Time for each step in the horizon

Explanation: PRED\_TIME is the prediction time of a controller beyond the control horizon. PRED\_TIME is typically set to a larger value than CTRL\_TIME to reach steady state conditions but also have fine resolution for near term movement of MVs. When CSV\_READ is on and the horizon time points are specified from the data file, the CTRL\_TIME and PRED\_TIME are set equal to the time increment of the first time step.

#### 4.4.44 REDUCE

Type: Integer, Input

Default Value: 0

Description: Number of pre-processing cycles to identify equations or variables to eliminate

Explanation: REDUCE is the number of cycles of pre-solve analysis before sending the problem to a solver. The analysis eliminates variables and equations with the following characteristics:

- variables that don't belong to an equation or objective
- equations with assignments such as  $x=2.5$  (set to value and fix)
  - identified with a single non-zero in Jacobian row
  - set variable equal to zero, evaluate residual
  - then set  $x = -\text{resid}/\text{jac}$  (when  $\text{abs}(\text{jac}) > \text{tolerance}$ )
  - check that upper or lower limits are not violated
- equations that connect two variables  $y = z$  (merge)
  - set variables equal to zero, evaluate residual
  - if  $\text{abs}(\text{residual}) \sim 0$  and  $\text{abs}(\text{jac}_1 - \text{jac}_2) \sim 0$ , merge
- independent blocks of linear equations (not yet implemented)
  - perform Lower Block Triangularization (LBT)
  - analyze independent blocks
  - if equation blocks are linear then solve and fix

If no variables are left (all reduced) then APMonitor reports a successful solution without sending the problem to a solver. When no variables or equations are eliminated, the remainder of the REDUCE cycles are skipped. REDUCE has the potential to present a more dense and smaller problem to the solver but may also require more pre-processing time that is more efficiently utilized by the solver.

#### 4.4.45 REPLAY

Type: Integer, Input

Default Value: 0

Description: Row counter for data in replay.csv

Explanation: REPLAY is a row indicator that is incremented each cycle when  $\text{REPLAY} \geq 1$ . When replay mode is activated, data from successive rows in replay.csv are inserted into the file measurements.dbs. The application solves and then REPLAY is incremented by 1. On the next cycle, measurements.dbs is populated from the next row and the cycle repeats. REPLAY is an efficient way of loading large amounts of data into an application without needing to load each measurement individually.

#### 4.4.46 REQCTRLMODE

Type: Integer, Input

Default Value: 3

Description: Requested control mode: 1=simulate, 2=predict, 3=control

Explanation: REQCTRLMODE is the requested controller mode as an input for the application. The requested control mode (REQCTRLMODE) is set as an input to the desired level of control but sometimes the CTRLMODE is not able to match the request because of a failed solution, a critical MV is OFF, or other checks with the application. REQCTRLMODE level of 0 indicates that the program should not run and the program terminates without attempting a solution. REQCTRLMODE level of 1 (cold mode) indicates that the program should be run as a simulator with all STATUS values turned off on FVs, MVs, and CVs. REQCTRLMODE level of 2 (warm mode) indicates that the application should calculate control actions but only after the second cycle. This mode is commonly used to observe anticipated control actions before the controller is activated to level 3. REQCTRLMODE level of 3 means that the controller should be turned ON and implement changes to the process.

#### 4.4.47 RTOL

Type: Real, Input

Default Value: 1.0e-6

Description: Equation solution tolerance

Explanation: RTOL is the relative inequality or equality equation tolerance for reporting a successful solution. A lower value of RTOL, such as 1e-8, will give a more precise answer but at the expense of more iterations. The default of 1e-6 is generally sufficient for most problems. However, there are times when the equation solution should be reported more precisely. Making RTOL too small may cause a bad solution to be reported because it surpasses the computer precision. RTOL and OTOL (relative tolerance for the objective function) should generally be adjusted together.

#### 4.4.48 SCALING

Type: Integer, Input

Default Value: 1

Description: Variable and Equation Scaling: 0=Off, 1=On (Automatic), 2=On (Manual)

Explanation: SCALING is an option to adjust variables by constants to make starting values equal to 1.0. Scaling of variables and equations generally improves solver convergence. Automatic and Internal scaling strategies are often implemented within solvers as well. The purpose of scaling is to avoid very large or very small values that may cause numerical problems with inverting matrices. Poor scaling may lead to ill-conditioned matrix inversions in finding a search direction. The difference between the largest and smallest eigenvalues should be within 12 orders of magnitude to avoid numerical problems. Scaling can be turned OFF (0) or ON (1). With SCALING=1, the scaling is taken from the initial guess values in the file. If the absolute value is less than one, no scaling is applied. With SCALING=2, the scaling is set for each variable individually.

#### 4.4.49 SENSITIVITY

Type: Integer, Input

Default Value: 1

Description: Sensitivity Analysis: 0=Off, 1=On

Explanation: SENSITIVITY determines whether a sensitivity analysis is performed as a post-processing step. The sensitivity analysis results are accessed either through the web-interface with the SENS tab or by retrieving the sensitivity.txt or sensitivity.htm files. The sensitivity is a measure of how the FV and MV values influence the objective function, SV, and CV final values. Another file, sensitivity\_all.txt contains sensitivities for all of the dependent variable values with respect to the FV and MV values.

#### 4.4.50 SEQUENTIAL

Type: Integer, Input

Default Value: 0

Description: Sequential solution method 0=Off 1=On

Explanation: SEQUENTIAL determines whether a the solution is attempted with a simultaneous (0) or sequential (1) approach. The sequential solution method solves independent decision variables in an outer loop from the system equations. This approach attempts to maintain feasibility from iteration to iteration but can significantly slow down the overall solution time. The SEQUENTIAL option can be used with any problem that has degrees of freedom such as

IMODE=2,3,5,6. When IMODE=7-9 (Sequential Dynamic Simulation, Estimation, and Control), the SEQUENTIAL option is automatically elevated to 1 and placed back to the default of 0 when the solution is completed.

#### 4.4.51 SOLVER

Type: Integer, Input

Default Value: 3

Description: Solver options: 0 = Benchmark All Solvers, 1-5 = Available Solvers Depending on License

Explanation: SOLVER selects the solver to use in an attempt to find a solution. There are free solvers: 1: APOPT, 2: BPOPT, 3: IPOPT distributed with the public version of the software. There are additional solvers that are not included with the public version and require a commercial license. IPOPT is generally the best for problems with large numbers of degrees of freedom or when starting without a good initial guess. BPOPT has been found to be the best for systems biology applications. APOPT is generally the best when warm-starting from a prior solution or when the number of degrees of freedom (Number of Variables - Number of Equations) is less than 2000. APOPT is also the only solver that handles Mixed Integer problems. Use option 0 to compare all available solvers.

#### 4.4.52 SOLVESTATUS

Type: Integer, Output

Default Value: 1

Description: Solution solve status: 1=good

Explanation: SOLVESTATUS is an indication of whether the solver returns a successful solution (1) or is unsuccessful at finding a solution (0). The solver may be unsuccessful for a variety of reasons including reaching a maximum iteration limit, an infeasible constraint, or an unbounded solution.

#### 4.4.53 SOLVETIME

Type: Real, Output

Default Value: 1.0

Description: Solution time (seconds)

Explanation: SOLVETIME is the amount of time in seconds dedicated to solving the problem with the solver. This is less than the overall time required for the entire application because of communication overhead, processing of inputs, and writing the solution files. The overall time can be reduced by setting WEB=0 to avoid writing web-interface files when they are not needed.

#### 4.4.54 SPECS

Type: Integer, Input

Default Value: 1

Description: Specifications from restart file: 1=ON, 0=OFF

Explanation: The default specifications of fixed or calculated are indicated in the restart t0 files that store prior solutions for warm starting the next solution. The SPECS option indicates whether the specifications should be read from the t0 file (ON) or ignored (OFF) when reading the t0 file for initialization.

#### 4.4.55 SPC\_CHART

Type: Integer, Input

Default Value: 0

Description: Statistical Process Control chart 0=OFF 1=add +/- 3 set point limits (red lines) 2=add +/- 2 set point limits (yellow lines) 3=add +/- 1 set point limits (green lines)

Explanation: SPC\_CHART is a web-interface trend option to create Statistical Process Control (SPC) style charts for Controlled Variables (CVs). When SPC\_CHARTS=0, there are no additional limits placed on the trend. As SPC\_CHARTS is increased by 1, there are additional ranges added to the CV plots. With a level of 1, new lines at +/- 3 SPHI-SPLO are added to the plot as red upper and lower control limits. With a level of 2, new lines at +/- 2 SPHI-SPLO are added to the plot as yellow upper and lower control limits. With a level of 1, new lines at +/- 1 SPHI-SPLO are added to the plot as green upper and lower control limits. Each level adds an additional two lines.

#### 4.4.56 STREAM\_LEVEL

Type: Integer, Input

Default Value: 0

Description: Stream level options 0=Mass Balance 1=Mass, Mole, and Energy Balances

Explanation: STREAM\_LEVEL controls the amount of detailed contained in flowsheet models through OBJECT declarations. At the basic level (0), only mass balance equations are solved. Variables for each stream are mass flow rate and mass fractions of all species declared in the COMPOUNDS section of the model. The last mass fraction is automatically set to make the summation equal to 1.0. At more the more advanced level (1), mole and energy balances are added. The higher stream level adds temperature, pressure, enthalpy, mole fractions, volumetric flow, density, and concentration.

#### 4.4.57 TIME\_SHIFT

Type: Integer, Input

Default Value: 1

Description: Time shift for dynamic problems: 1=ON, 0=OFF

Explanation: TIME\_SHIFT indicates the number of time steps that a prior solution should be shifted to provide both initial conditions and an initial guess for a dynamic simulation or optimization problem. When TIME\_SHIFT = 1 (default), the solution is shifted by one time step. For real-time applications, the cycle time of the solutions should correspond to the first time increment of the application. The first time increment is either set in the CSV file in the time column or else with CTRL\_TIME. Failure to synchronize the frequency of solution and the first application step size results in dynamic mismatch. The TIME\_SHIFT is set to 0 if the solution should not be shifted over from a prior solution. The TIME\_SHIFT can be set to >=2 when multiples of the controller cycle time have elapsed since the prior solution.

#### 4.4.58 WEB

Type: Integer, Input

Default Value: 1

Description: Generate HTML pages: 1=ON, 0=OFF

Explanation: WEB is an option that controls how much web-content is produced. A value of 0 indicates that a browser interface should not be created. This option can improve overall application speed because the web interface files are not created. The default value is 1 to create a single instance of the web interface when the program computes a solution. When DIAGLEVEL $\geq$ 2, the web interface is also created before the program runs to allow a user to view the initial guess values.

#### **4.4.59 WEB\_MENU**

Type: Integer, Input

Default Value: 1

Description: Generate HTML navigation menus: 1=ON, 0=OFF

Explanation: WEB\_MENU turns OFF (0) or ON (1) the display of a navigation pane at the top of each auto-generated schematic. WEB\_MENU should generally be ON (1) but can be turned off to not give options to the end user to access certain configuration options that are normally reserved for a more advanced user.

#### **4.4.60 WEB\_REFRESH**

Type: Integer, Input

Default Value: 10

Description: Automatic refresh rate on HTML pages (default 10 minutes)

Explanation: WEB\_REFRESH is an internal time of the auto-generated web-interface to automatically reload the page. The default value is 10 minutes although it is not typically necessary to update the web-page. New values are automatically loaded to the web-page through AJAX communication that updates the parts of the page that need to be updated.

#### **4.4.61 WEB\_PLOT\_FREQ**

Type: Integer, Input

Default Value: 1

Description: Automatic refresh rate on web interface plots

Explanation: WEB\_PLOT\_FREQ is an internal time in seconds to refresh the web-interface plots. This option does not automatically reload the page but just the plot within the web-page. The default value is 1 second but this value can be increased to lessen the network load as data is repeatedly sent from the server to the web-interface. Processes with slow dynamics or long cycle times may not need the fast refresh rates. If an error message appears, it may indicate that the plot source files were in the process of being rewritten when the new request for data was initiated. The error message is resolved by reloading the web-page.

### **4.5 Tuning Parameters**

Local Options: DBS Parameters for Variables

The following is a list of parameters that may be found in the DBS file for variables listed in the INFO file. It is a complete list of the configuration parameters for FV, MV, SV, CV type parameters and variables. Each section includes an indication of the variable type (Integer or Real), the default value, data flow, and description.

### 4.5.1 AWS

Local Options | Global Options

Type: Floating Point, Output

Default Value: 0

Description: Anti-Windup Status for a Manipulated Variable 0: Not at a limit 1: An upper or lower bound is reached

Explanation: Anti-Windup Status (*AWS*) is terminology borrowed from classical controls such as Proportional Integral Derivative (PID) controllers. Anti-Windup refers to the integral action that is paused when the controller reaches a saturation limit. An example of a saturation limit is a valve that is limited to 0-100% open. If the controller requests -10%, the valve is still limited to 0%. The *AWS* indication is useful to show when a controller is being driven by an optimization objective versus constraints that limit movement. A Key Performance Indicator (KPI) of many controllers is the fraction of time that a MV is not at an upper or lower bound limit.

### 4.5.2 BIAS

Type: Floating Point, Input/Output

Default Value: 0.0

Description: Additive correction factor to align measurement and model values for Controlled Variables (CVs) *BIAS* is additive factor that incorporates the difference between the current measured value and the initial condition of the controller. *FSTATUS* determines how much of the raw measurement is used to update the value of *MEAS*. A feedback status of 0 indicates that the measurement should not be used and the *BIAS* value is kept at the initial value of 0. A feedback status of 1 uses all of the measurement in updating *MEAS*. A feedback status in between 0 and 1 updates *MEAS* with a fractional contribution from *LSTVAL* and the new measurement. The value of *BIAS* is updated from *MEAS* and the unbiased model prediction (*Model\_u*).

$$BIAS = MEAS - Model_u$$

The *BIAS* is added to each point in the horizon and the controller objective function drives the biased model (*Model\_b*) to the requested set point range.

$$Model_b = Model_u + BIAS$$

The value of *BIAS* can also be set to an external value by setting the option *BIAS* option directly and setting *FSTATUS* to 0 (OFF).

### 4.5.3 COST

Type: Real, Input

Default Value: 0.0

Description: Cost weight: (+)=minimize, (-)=maximize

Explanation: Multiplies the parameter by the *COST* value specified. This is used to scale the terms in the objective function. It is important that each term in the objective function is scaled to be of the same order of magnitude to ensure that the optimizer considers each of them (unless different weighting is specifically desired).

#### 4.5.4 CRITICAL

Type: Integer, Input

Default Value: 0

Description: Critical: 0=OFF, 1=ON

Explanation: Turns the application off ( *REQCTRLMODE* =1) if the instrument that provides the measurement has a *PSTATUS* =0 (bad measurement). A critical measurement has this flag on to give control back to the operator if the measurement fails to deliver a good value.

#### 4.5.5 DCOST

Type: Real, Input

Default Value: 0.00001

Description: Delta cost penalty for MV movement

Explanation: Adds a term to the objective function that gives a minor penalty for changing the MV. The weight of the penalty is adjusted with the input value. This is useful for systems where excessive movement to the MV causes damage to equipment or undesirable results. By assigning a weight that is small in comparison to the objective function value, optimal performance is achieved while changing the MV only when necessary.

$$objective += \sum_{i=1} \|x_{i-1} - x_i\|_p$$

Where  $p$  is equal to *EV\_TYPE* (for *IMODE*=5or8) or *CV\_TYPE* (for *IMODE*=6or9).

#### 4.5.6 DMAX

Type: Real, Input

Default Value: 1.0e20

Description: Delta MV maximum step per horizon interval

Explanation: Applies a hard constraint that prevents the MV from being changed by more than the specified value in one time step. This can be used to prevent large jumps in the MV value in the case where that is either undesirable or infeasible. The time step is defined as the length of the first time step in the csv file.

#### 4.5.7 DMAXHI

Type: Real, Input

Default Value: 1.0e20

Description: Delta MV positive maximum step per horizon interval

Explanation: Like *DMAX*, but only with positive changes. Applies a hard constraint that prevents the MV from being changed by more than the specified value in one time step, but this constraint only applies to increases in the MV value. This can be used to prevent large jumps in the MV value in the case where that is either undesirable or infeasible.

### 4.5.8 DMAXLO

Type: Real, Input

Default Value: -1.0e20

Description: Delta MV negative maximum step per horizon interval

Explanation: Like *DMAX*, but only with negative changes. Applies a hard constraint that prevents the MV from being changed by more than the specified value in one time step, but this constraint only applies to decreases in the MV value. This can be used to prevent large jumps in the MV value in the case where that is either undesirable or infeasible.

### 4.5.9 DPRED

Type: Real, Output

Default Value: 0.0

Description: Delta prediction changes for each step

Explanation: Changes in the manipulated variables (MVs) are listed for the first 10 steps of the horizon including *DPRED[1]*, *DPRED[2]*, etc. Values of zero indicate that there are no changes. With *REQCTRLMODE=1* (COLD), all *DPRED* values are zero. With *REQCTRLMODE=2* (WARM), only *DPRED[1]* is required to be zero but the other segments may be non-zero. With *REQCTRLMODE=3* (CONTROL), the first *DPRED* value is changing.

### 4.5.10 FSTATUS

Type: Real, Input

Default Value: 1.0

Description: Feedback status: 1=ON, 0=OFF

Explanation: Determines how much of the measurement (*MEAS*) to use in updating the values in the model. A feedback status of 0 indicates that the measurement should not be used either in estimation or in updating a parameter in the model. A feedback status of 1 uses all of the measurement. A feedback status in between updates the model OR parameter value (*x*) according to the formula:

$$x = LSTVAL * (1 - FSTATUS) + MEAS * FSTATUS$$

### 4.5.11 FDELAY

Type: Integer, Input

Default Value: 0

Description: Feedback delay: 0=No Delay, >=1 horizon steps for delay

Explanation: The feedback delay places the measurement at the appropriate point in the horizon for dynamic estimation. Typical examples are laboratory measurement or gas chromatographs that report measurements that were taken in the past, usually with a 10 min - 2 hour delay. When the new value is reported, it should be placed at the appropriate point in the data time horizon. *FDELAY* is the number of horizon steps in the past where the measurement was actually taken.

### 4.5.12 LOWER

Type: Real, Input

Default Value: -1.0e20

Description: Lower bound

Explanation: *LOWER* is the lower limit of a variable. If the variable guess value is below the lower limit, it is adjusted to the lower limit. The lower limit is also checked with the upper limit to ensure that it is less than or equal to the upper limit. If the lower limit is equal to the upper limit, the variable is fixed at that value.

### 4.5.13 LSTVAL

Type: Real, Output

Default Value: 1.0

Description: Last value from previous solution

Explanation: The last value (*LSTVAL*) is the value from the prior solution of the optimization problem or simulation.

### 4.5.14 MEAS

Type: Real, Input

Default Value: 1.0

Description: Measured value

Explanation: The measurement of a variable or parameter. The value of *MEAS* is initialized to the initial model value. The *MEAS* value is used in the application if *FSTATUS* is greater than zero, but not when *FSTATUS*=0.

*MEAS* must be a scalar and only one measurement is loaded in each *solve()* command. If multiple measurements are needed, they can be loaded through the *VALUE* attribute in their respective locations.

### 4.5.15 MEAS\_GAP

Type: Real, Input

Default Value: 1.0

Description: Deadband for noise rejection of measurements in MHE

Explanation: Used in estimation problems with *EV\_TYPE* =1 (11-norm objective). The measurement gap (*MEAS\_GAP*) defines a dead-band region around the measurement. If the model prediction is within that dead-band, there is no objective function penalty. Outside of that region, there is a linear penalty specified with the *WMEAS* parameter. The *WMODEL* parameter is the weighting given to deviation from the prior model prediction but does not have a deadband around the prior model prediction. The gap is only around the measured values.

### 4.5.16 MODEL

Type: Real, Output

Default Value: 1.0

Description: Model predicted value

Explanation: The MODEL value is a property of SV (State Variable) and CV (Controlled Variable) types. It is the predicted value of the current time. The current time is the first time step for a simulator or controller and the last value in the horizon for estimation.

#### 4.5.17 MV\_STEP\_HOR

Type: Integer, Input

Default Value: 0 (for global *MV\_STEP\_HOR*) or 1 (for MV(#).MV\_STEP\_HOR)

Description: Step length for manipulated variables: 0 uses global *MV\_STEP\_HOR* as default

Explanation: The manipulated variable step horizon (MV\_STEP\_HOR) is by default to allow the MV to be adjusted every time set of the collocation. There are cases where the MV should not move every time step but should be constrained to move only a certain multiple of the collocation time step. With MV\_STEP\_HOR = 2, the manipulated variable is allowed to move on the first step and every other step thereafter. MV\_STEP\_HOR = 5, the manipulated variable is allowed to move on the first step and every 5th step thereafter. There is also a global parameter *MV\_STEP\_HOR* that is used as a global configuration for all MVs when the individual MV option is set to 0.

#### 4.5.18 NEWVAL

Type: Real, Output

Default Value: 1.0

Description: New value implemented by the estimator or controller (NEWVAL = MEAS when not in control)

Explanation: The new value of the parameter estimate (FV) or manipulated variable (MV). This value is taken from the first step of the controller or the last step of the estimator. The NEWVAL is set equal to the measured value if the FV or MV status is off and the FSTATUS (feedback status) is ON (1).

#### 4.5.19 NXTVAL

Type: Real, Output

Default Value: 1.0

Description: Next value that the estimator or controller would implement if CTRLMODE=3.

Explanation: The next value (NXTVAL) to be implemented by the controller. This is especially useful for a controller in WARM mode (CTRLMODE=2) where no values are changed on the first step (still in manual mode) but the control actions are computed beyond the first step. This is a useful mode to inspect the controller performance before it is turned on.

#### 4.5.20 OBJPCT

Type: Real, Output

Default Value: 0.0

Description: Percent of objective function contribution considering all SV and CV variables

Explanation: The objective function percent is useful to see which controlled variables (CVs) are contributing the most to the controller overall objective function. If one of the CVs has a high OBJPCT, it may be dominating the controller action and the tuning factors WSP (CV\_TYPE=2) or WSPHI/WSPLO (CV\_TYPE=1) should be adjusted accordingly.

### 4.5.21 OSTATUS

Type: Integer, Output

Default Value: 0

Description: Bit encoding for status messages

Explanation: Status messages encoded in binary form for transfer and decoding. This is deprecated and will be removed in a future release.

### 4.5.22 OSTATUSCHG

Type: Integer, Output

Default Value: 0

Description: Change in bit encoding for status messages

Explanation: Change of status messages, encoded in binary form for transfer and decoding. This is deprecated and will be removed in a future release.

### 4.5.23 PRED

Type: Real, Output

Default Value: 1.0

Description: Prediction horizon

Explanation: The first predictions of a state (SV) or controlled (CV) variable. The number of PRED values is limited to the first 10 but can be less with a shorter horizon. PRED[0] is the initial condition while PRED[1] is the first predicted step. The other values PRED[2], PRED[3], ... , PRED[10] are the predicted model values up to a horizon of 10 time points.

### 4.5.24 PSTATUS

Type: Integer, Input

Default Value: 1

Description: Instrument status: 1=GOOD, 0=BAD

Explanation: An indication of the instrument health. If PSTATUS is 0 then the instrument is determined to be bad and the measurement should not be used. By default, all instruments are assumed to be reporting good values.

### 4.5.25 REQONCTRL

Type: Integer, Input

Default Value: 0

Description: Required for control mode to be ON (3): 1=ON, 0=OFF

Explanation: Certain Manipulated Variables (MVs) and Controlled Variables (CVs) are critical to the operation of the entire application. When any of the MVs or CVs with REQONCTRL are turned off, the entire application is turned off (CTRLMODE=1). The requested control mode (REQCTRLMODE) is the requested controller mode but this option downgrades the controller to a simulation mode if a critical MV or CV is OFF.

#### 4.5.26 SP

Type: Real, Input

Default Value: 0.0

Description: Set point for squared error model

Explanation: The target value for a controller that is using a squared error objective (single trajectory track). The setpoint (SP) is the final target value.

#### 4.5.27 SPHI

Type: Real, Input

Default Value: 1.0e20

Description: Set point high for linear error model

Explanation: The upper range of the target region (dead-band) for a controller that is using an l1-norm error objective. The setpoint high (SPHI) is the upper final target value.

#### 4.5.28 SPLO

Type: Real, Input

Default Value: -1.0e20

Description: Set point low for linear error model

Explanation: The lower range of the target region (dead-band) for a controller that is using an l1-norm error objective. The setpoint low (SPLO) is the lower final target value.

#### 4.5.29 STATUS

Type: Integer, Input

Default Value: 0

Description: Status: 1=ON, 0=OFF

Explanation: The STATUS specifies when a parameter (FV or MV) that is normally fixed (OFF) can become calculated (ON). Similarly, STATUS set to ON, allows a controlled variable (CV) to be included as a model predictive controller set point target or steady state optimizer target. The STATUS value indicates whether that variable should be included in the optimization (ON) or is merely a fixed input or prediction (OFF). It is acceptable to have only a subset of parameters (FVs or MVs) or variables (CVs) with STATUS set to ON. The STATUS can be turned ON or OFF for each cycle of the controller as needed without disrupting the overall application. An estimator uses STATUS for FVs and MVs but uses FSTATUS (not STATUS) to determine when measurements are used.

#### 4.5.30 TAU

Type: Real, Input

Default Value: 60.0

Description: Time constant for controlled variable response

Explanation: The time constant is a tuning parameter for the speed of response of a reference trajectory. When the set point is stepped to a new value, the time constant (TAU) adjusts the speed of response with  $SP_{tr} = (1 - \exp(-t/TAU))(SP_{new} - SP_{old}) + SP_{old}$  where  $SP_{old}$  is the prior set point,  $SP_{new}$  is the new set point,  $t$  is the time, TAU is the time constant, and  $SP_{tr}$  is the resultant trajectory.

### 4.5.31 TIER

Type: Integer, Input

Default Value: 1

Description: Tiered order of Manipulated Variables (MVs) and Controlled Variables (CVs)

Explanation: TIER is an ascending order of precedence for optimization. Tuning an application with multiple objectives can be challenging to coordinate the weights of competing objectives although there is a clear rank priority order. TIER gives the option to split the degrees of freedom into multiple sub-optimization problems. The highest priority values are optimized first while the subsequent priority values are optimized as a next step. Valid TIER values for MVs and CVs are between 1 and 100. There are up to 100 optimization levels and individual MVs / CVs must be at the same TIER value to be included in the sub-optimization problem. The STATUS must also be ON (1) for an MV to be a degree of freedom. The STATUS must also be ON (1) for an CV to be included in the objective function. If there is a sub-optimization problem that has no MV degrees of freedom, a warning message is displayed.

### 4.5.32 TR\_OPEN

Type: Real, Input

Default Value: 1.0

Description: Initial trajectory opening ratio (0=ref traj, 1=tunnel, 2=funnel)

Explanation: TR\_OPEN controls the trajectory opening for  $CV\_TYPE = 1$ . It is the ratio of opening gap to the final gap of  $SP_{HI} - SP_{LO}$ . A value of  $TR\_OPEN = 2$  means that the initial trajectory is twice the width of the final gap of  $SP_{HI} - SP_{LO}$ . With  $TR\_OPEN = 0$ , the initial trajectory starts at the same point and widens with a first order response as specified by TAU to final destinations of SPHI and SPLO. Each CV can have a different TR\_OPEN.

### 4.5.33 TR\_INIT

Type: Integer, Input

Default Value: 0

Description: Setpoint trajectory initialization (0=dead-band, 1=re-center with coldstart/out-of-service, 2=re-center always)

Explanation: TR\_INIT is an option to specify how the initial conditions of the controlled variable's (CV) setpoint reference trajectory should change with each cycle. The trajectory is set by TAU. An option of 0 specifies that the initial conditions should start at SPHI and SPLO, creating an unchanging target over the horizon. An option of 1 makes the initial conditions equal to the current process variable value only on coldstart ( $COLDSTART \geq 1$ ) or with  $CTRLMODE \leq 2$  when the controller is out of service. Otherwise, the reference trajectory is updated from the first step of the prior solution. When  $TR\_INIT=2$ , the reference trajectory realigns to the variable's initial condition with each cycle. Each CV can have a different TR\_INIT. The trajectory is also influenced by TR\_OPEN.

### 4.5.34 UPPER

Type: Real, Input

Default Value: 1.0e20

Description: Upper bound

Explanation: *UPPER* is the the upper limit of a variable. If the variable guess value is above the upper limit, it is adjusted to the upper limit before it is given to the solver. The upper limit is also checked with the lower limit (*LOWER*) to ensure that it is greater than or equal to the lower limit. If the upper limit is equal to the lower limit, the variable is fixed at that value.

### 4.5.35 VALUE

Type: Real, Input/Output

Default Value: 1

Description: Value of the variable

Explanation: ..\_vdl:

### 4.5.36 VDL

Type: Real, Input

Default Value: 1.0e20

Description: Delta validity limit

Explanation: *VDL* is the maximum change of a measured value before it is considered an unrealistic change. The change in measured values is recorded at every cycle of the application and compared to the *VDL* limit. Validity limits are placed to catch instrument errors that may otherwise create bad inputs to the application. If a delta validity limit is exceeded, the action is to either freeze the measured value at the last good value (*VLACTION* =0) or change the measured value by a maximum of *VDL* in the direction of the bad measurement (*VLACTION* =1). Another way to minimize the impact of unrealistic changes in measurements is to set *FSTATUS* between 0 and 1 with values closer to 0 becoming insensitive to measurement changes.

### 4.5.37 VLACTION

Type: Integer, Input

Default Value: 0

Description: Validity Limit Action

Explanation: *VLACTION* is the validity limit action when vdl is exceeded. The change in measured values is recorded at every cycle of the application and compared to the *VDL* limit. Validity limits are placed to catch instrument errors that may otherwise create bad inputs to the application. If a delta validity limit is exceeded, the action is to either freeze the measured value at the last good value (*VLACTION*=0) or change the measured value by a maximum of *VDL* in the direction of the bad measurement (*VLACTION*=1).

#### 4.5.38 VLHI

Type: Real, Input

Default Value: 1.0e20

Description: Upper validity limit

Explanation: *VLHI* is the upper validity limit for a measured value. Validity limits are one way to protect an application against bad measurements. This gross error detection relies on a combination of change values and absolute limits to determine when a measurement should be rejected. If *VLHI* is exceeded, the measured value is placed at *VLHI* or the maximum move allowed by *vdvl* when *VLACTION* =1. If *VLACTION* =0, there is no change in the measured value when a limit ( *vdvl*, *VLHI*, *VLLO*) is exceeded.

#### 4.5.39 VLLO

Type: Real, Input

Default Value: -1.0e20

Description: Lower validity limit

Explanation: *VLLO* is the lower validity limit for a measured value. Validity limits are one way to protect an application against bad measurements. This gross error detection relies on a combination of change values and absolute limits to determine when a measurement should be rejected. If the *VLLO* limit is crossed, the measured value is placed at *VLLO* or the maximum move allowed by *VDVL* when *VLACTION*=1. If *VLACTION*=0, there is no change in the measured value when a limit (*VDVL*, *VLHI*, *VLLO*) is exceeded.

#### 4.5.40 WMEAS

Type: Real, Input

Default Value: 20.0

Description: Objective function weight on measured value

Explanation: A weighting factor to penalize deviation of current model predictions from measured values. This is used in estimation applications ( *Modes* =2, 5, or 8) where the penalty. The infinite estimation horizon approximation is especially useful for systems that have weakly observable or unobservable states. A higher *WMODEL* can also help to reduce the aggressiveness of the estimator in aligning with the measurements by balancing with a penalty against shifting too far from the prior predictions. The *WMODEL* value should never be equal to or larger than the *WMEAS* value for *EV\_TYPE* =1 (11-norm). A *WMODEL* value higher than *WMEAS* will ignore measured values in favor of matching prior model predictions.

#### 4.5.41 WMODEL

Type: Real, Input

Default Value: 2.0d0

Description: Objective function weight on model value

Explanation: A weighting factor to penalize deviation of current model predictions from prior model predictions. This is used in estimation applications (*IMODE*=2, 5, or 8) where the penalty from a prior model prediction is a “forgetting factor” that approximates an infinite estimation horizon or favors prior predictions. The infinite estimation horizon approximation is especially useful for systems that have weakly observable or unobservable states. A higher *WMODEL* can also help to reduce the aggressiveness of the estimator in aligning with the measurements by balancing

with a penalty against shifting too far from the prior predictions. The WMODEL value should never be equal to or larger than the WMEAS value for EV\_TYPE=1 (11-norm). A WMODEL value higher than WMEAS will ignore measured values in favor of matching prior model predictions.

#### 4.5.42 WSP

Type: Real, Input

Default Value: 1.0

Description: Objective function weight on set point for squared error model

Explanation: A weighting factor to penalize a squared error from the setpoint trajectory with final target SP. The weighting factor is positive to drive the response to the SP trajectory and negative to drive it away from the SP. A negative WSP is highly unlikely and the value should generally be positive.

#### 4.5.43 WSPHI

Type: Real, Input

Default Value: 1.0

Description: Objective function weight on upper set point for linear error model

Explanation: A weighting factor to penalize deviation above the upper setpoint trajectory with final target SPHI. If there is no penalty to cross the upper setpoint, WSPHI can be set to zero.

#### 4.5.44 WSPLO

Type: Real, Input

Default Value: 1.0

Description: Objective function weight on lower set point for linear error model

Explanation: A weighting factor to penalize deviation below the lower setpoint trajectory with final target SPLO. If there is no penalty to cross the lower setpoint trajectory, WSPLO can be set to zero.

## 4.6 Manipulated Variable Options

The following is a list of parameters associated with FVs and MVs.

### 4.6.1 FV Options

This is a list of all available options for FVs and their default values:

*CRITICAL* = 0

*DMAX* = 1.0e20

*DMAXHI* = 1.0e20

*DMAXLO* = -1.0e20

*FSTATUS* = 1.0

*LOWER* = -1.0e20  
*LSTVAL* = 1.0  
*MEAS* = 1.0  
*NEWVAL* = 1.0  
*PSTATUS* = 1  
*STATUS* = 1  
*UPPER* = 1.0e20  
vdl = 1.0e20  
*VLACTION* = 0  
*VLHI* = 1.0e20  
*VLLLO* = -1.0e20

## 4.6.2 MV Options

This is a list of all available options for MVs and their default values:

*AWS* = 0  
*COST* = 0.0  
*CRITICAL* = 0  
*DCOST* = 0.00001  
*DMAX* = 1.0e20  
*DMAXHI* = 1.0e20  
*DMAXLO* = -1.0e20  
*DPRED* = 0.0  
*FSTATUS* = 1.0  
*LOWER* = -1.0e20  
*LSTVAL* = 1.0  
*MEAS* = 1.0  
*MV\_STEP\_HOR* = 0  
*NEWVAL* = 1.0  
*NXTVAL* = 1.0  
*PRED* = 1.0  
*PSTATUS* = 1  
*REQONCTRL* = 0  
*STATUS* = 1  
*TIER* = 1  
*UPPER* = 1.0e20  
vdl = 1.0e20

*VLACTION* = 0  
*VLHI* = 1.0e20  
*VLLO* = -1.0e20

## 4.7 Controlled Variable Options

### 4.7.1 SV Options

This is a list of all available options for SVs and their default values:

*FSTATUS* = 0  
*LOWER* = -1.0e20  
*MEAS* = 1.0  
*MODEL* = 1.0  
*PRED* = 1.0  
*UPPER* = 1.0e20

### 4.7.2 CV Options

This is a list of all available options for CVs and their default values:

*BIAS* = 0.0  
*COST* = 0.0  
*CRITICAL* = 0  
*FDELAY* = 0  
*FSTATUS* = 0  
*LOWER* = -1.0e20  
*LSTVAL* = 1.0  
*MEAS* = 1.0  
*MEAS\_GAP* = 1.0e-3  
*MODEL* = 1.0  
*PRED* = 1.0  
*PSTATUS* = 1  
*SP* = 0.0  
*SPHI* = 1.0e20  
*SPLO* = -1.0e20  
*STATUS* = 0  
*TAU* = 60.0  
*TIER* = 1  
*TR\_INIT* = 0

```

TR_OPEN = 1.0
UPPER = 1.0e20
vdl = 1.0e20
VLACTION = 0
VLHI = 1.0e20
VLLO = -1.0e20
WMEAS = 20.0
WMODEL = 2.0
WSP = 20.0
WSPHI = 20.0
WSPLO = 20.0

```

## 4.8 Model Building Functions

### 4.8.1 Model Building

**m = GEKKO(remote=True, [server], [name]):**

Creates a GEKKO model *m*.

If *remote* is *True*, the problem is sent to *self.server* to be solved. If *False*, GEKKO looks for local binaries of APMonitor.

**c = m.Const(value, [name]):**

**p = m.Param([value], [name])**

**v = m.Var([value], [lb], [ub], [integer], [name])**

**m = m.MV([value], [lb], [ub], [integer], [name])**

**f = m.FV([value], [lb], [ub], [integer], [name])**

**s = m.SV([value] [lb], [ub], [integer], [name])**

**c = m.CV([value] [lb], [ub], [integer], [name])**

**i = m.Intermediate(equation, [name])**

**eq = m.Equation(equation)**

Add a constraint *equation* built from GEKKO Parameters, Variables and Intermediates, and python scalars. Valid operators include python math and comparisons (+, -, \*, /, \*\*, ==, <, >). Available functions are listed below in *Equation Functions*.

**[eqs] = m.Equations(equations)**

Accepts a list or array of equations.

**classmethod m.Obj(obj)**

The problem objective to minimize. If multiple objective are provided, they are summed.

**m.time**

Sets the time array indicating the discrete elements of time discretization for dynamic modes (*IMODE* > 3). Accepts a python list of a numpy array.

**classmethod** `dt()`

Ordinary differential equations are specified by differentiating a variable with the `dt()` method. For example, velocity  $v$  is the derivative of position  $x$ :

```
m.Equation( v == x.dt() )
```

Discretization is determined by the model `time` attribute. For example, `m.time = [0,1,2,3]` will discretize all equations and variables at the 4 points specified. Only ordinary differential equations discretized by time are available internally. Other discretization must be performed manually.

**a = m.Array(type, dimension, \*\*args)**

Create an  $n$ -dimensional array (as defined in tuple input `dimension`) of GEKKO variables of type `type`.

The optional keyword arguments (`**args`) are applied to each element of the array.

**classmethod** `m.solve` (`disp=True`, `debug=False`)

Solve the optimization problem.

This function has these substeps:

- Validates the model and write `.apm` file
- Validate and write `.csv` file
- Write options to `.dbs` file
- Solve the problem using `apm.exe`
- Load results into python variables.

If `disp` is `True`, APM and solve output are printed.

If `debug` is `True`, variable names are checked for problems, tuning parameters are checked for common errors, and user-defined input options are compared against options used by APM. This is useful in debugging strange results.

If `GUI` is `True`, the results of this solve are sent to the GUI. If the GUI is not open yet, the GUI object is created, the server is spawned and the browser client is launched.

**classmethod** `m.Connection` (`var1`, `var2`, `pos1=None`, `pos2=None`, `node1='end'`, `node2='end'`)

`var1` must be a GEKKO variable, but `var2` can be a static value. If `pos1` or `pos2` is not `None`, the associated variable must be a GEKKO variable and the position is the (0-indexed) time-discretized index of the variable.

Connections are processed after the parameters and variables are parsed, but before the initialization of the values. Connections are the merging of two variables or connecting specific nodes of a discretized variable. Once the variable is connected to another, the variable is only listed as an alias. Any other references to the connected value are referred to the principal variable (`var1`). The alias variable (`var2`) can be referenced in other parts of the model, but will not appear in the solution files.

**classmethod** `m.fix` (`var`, `pos`, `val`)

This function facilitates the `Connection` function when `var2` is a static value (`val`).

**m.solver\_options**

A list of strings to pass to the solver; one string for each option name and value. For example:

```
m = GEKKO()
m.solver_options = ['max_iter 100', 'max_cpu_time 100']
```

## 4.8.2 Equation Functions

Special function besides algebraic operators are available through GEKKO functions. These must be used (not numpy or other equivalent functions):

**classmethod** `m.sin` (*other*)

**classmethod** `m.cos` (*other*)

**classmethod** `m.tan` (*other*)

**classmethod** `m.asin` (*other*)

**classmethod** `m.acos` (*other*)

**classmethod** `m.atan` (*other*)

**classmethod** `m.sinh` (*other*)

**classmethod** `m.mcosh` (*other*)

**classmethod** `m.tanh` (*other*)

**classmethod** `m.exp` (*other*)

**classmethod** `m.log` (*other*)

**classmethod** `m.log10` (*other*)

**classmethod** `m.sqrt` (*other*)

## 4.8.3 Pre-built Objects

**x, y, u = state\_space** (**A, B, C, D=None, discrete=False, dense=False**)

For State Space models, input SS matrices A,B,C, and optionally D. Returns a GEKKO array of states (SV) *x*, array of outputs (CV) *y* and array of inputs (MV) *u*. A,B,C and D must be 2-dimensional matrices of the appropriate size.

The *discrete* Boolean parameter indicates a discrete-time model, which requires constant time steps and 2 *NODES*. The *dense* Boolean parameter indicates if A,B,C,D should be written as dense or sparse matrices. Sparse matrices will be faster unless it is known that the matrices are very dense.

**classmethod** `m.cspline` (*x, y, x\_data, y\_data, bound\_x=False*)

Generate a 1d cubic spline with continuous first and seconds derivatives from arrays of *x* and *y* data which link to GEKKO variables *x* and *y* with a constraint that  $y=f(x)$ .

This function is currently only available through remote solves to the default server.

Inputs:

*x*: GEKKO variable

*y*: GEKKO variable

*x\_data*: array of *x* data

*y\_data*: array of *y* data that matches *x\_data*

*bound\_x*: boolean to state that *x* should be bounded at the upper and lower bounds of *x\_data* to avoid extrapolation error of the cspline.

**classmethod** `periodic(v)`

Makes the variable argument periodic by adding an equation to constrains  $v[\text{end}] = v[0]$ . This does not affect the default behavior of fixing initial conditions ( $v[0]$ ).

## 4.8.4 Internal Methods

These are the major methods used internal by GEKKO. They are not intended for external use, but may prove useful for highly customized applications.

**static** `build_model(self)`

Write the .apm model file for the executable to read. The .apm file contains all constants, parameters, variables, intermediates, equations and objectives. Single values and/or initializations, along with variable bounds, are passed through the .apm model file.

**static** `write_csv()`

Any array values are passed through the csv, including variable initializations. If `imode > 3` then `time` must be discretized in the csv.

**static** `generate_overrides_dbs_file()`

All global and local variable options are listed in the overrides database file.

**static** `load_json()`

Reads back global and variable options from the options.json file. Stores output and input/output options to the associated variable.

**static** `load_results()`

The executable returns variable value results in a json. This function reads the json and loads the results back into local python variables.

**static** `verify_input_options()`

Called when optional `solve` argument `verify_input=True`. Compares input options of the model and variables from GEKKO to those reported by APM to find discrepancies.

## 4.8.5 Internal Attributes

These are GEKKO model attributes used internally. They are not intended for external use, but may prove useful in advanced applications.

**server**

String representation of the server url where the model is solved. The default is `'http://xps.apmonitor.com'`. This is set by the optional argument `server` when intializing a model.

**remote**

Boolean that determines if solutions are offloaded to the server or executed locally.

**id****\_constants**

A python list of pointers to GEKKO Constants attributed to the model.

**\_parameters**

A python list of pointers to GEKKO Parameters, FVs and MVs attributed to the model.

**\_variables**

A python list of pointers to GEKKO Variables, SVs and CVs attributed to the model.

**\_intermediates**

A python list of pointers to GEKKO Intermediate variables attributed to the model.

**`_inter_equations`**

A python list of the explicit intermediate equations. The order of this list must match the order of intermediates in the *intermediates* attribute.

**`_equations`**

A python list of equations

**`_objectives`**

A python list of objective.

**`_connections`**

A python list of connections

**`csv_status`**

Set to 'generated' if any time, parameter or variable data is communicated through the csv file. Otherwise set to 'none'.

**`model_name`**

The name of the model as a string. Used in local temporary file name and application name for remote solves. This is set by the optional argument *name* when initializing a model. Default names include the model *id* attribute to maintain unique names.

**`_path`**

The absolute path of the temporary file used to store all input/output files for the APMonitor executable.

## 4.9 Examples

### 4.9.1 HS 71 Benchmark

$$\begin{aligned}
 & \min \\
 & x_1 x_4 (x_1 + x_2 + x_3) + x_3 \\
 & \quad \text{s.t.} \\
 & x_1 x_2 x_3 x_4 \geq 25 \\
 & x_1^2 + x_2^2 + x_3^2 + x_4^2 = 40 \\
 & 1 \leq x_1, x_2, x_3, x_4 \leq 5 \\
 & x_0 = (1, 5, 5, 1)
 \end{aligned}$$

This example demonstrates how to solve the HS71 benchmark problem using GEKKO:

```

from gekko import GEKKO

# Initialize Model
m = GEKKO(remote=True)

#help(m)

#define parameter
eq = m.Param(value=40)

#initialize variables
    
```

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```

x1,x2,x3,x4 = [m.Var() for i in range(4)]

#initial values
x1.value = 1
x2.value = 5
x3.value = 5
x4.value = 1

#lower bounds
x1.lower = 1
x2.lower = 1
x3.lower = 1
x4.lower = 1

#upper bounds
x1.upper = 5
x2.upper = 5
x3.upper = 5
x4.upper = 5

#Equations
m.Equation(x1*x2*x3*x4>=25)
m.Equation(x1**2+x2**2+x3**2+x4**2==eq)

#Objective
m.Obj(x1*x4*(x1+x2+x3)+x3)

#Set global options
m.options.IMODE = 3 #steady state optimization

#Solve simulation
m.solve() # solve on public server

#Results
print('')
print('Results')
print('x1: ' + str(x1.value))
print('x2: ' + str(x2.value))
print('x3: ' + str(x3.value))
print('x4: ' + str(x4.value))

```

## 4.9.2 Solver Selection

Solve  $y^2=1$  with APOPT solver. See APMonitor documentation or GEKKO documentation for additional solver options:

```

m = GEKKO()          # create GEKKO model
y = m.Var(value=2)  # define new variable, initial value=2
m.Equation(y**2==1) # define new equation
m.options.SOLVER=1  # change solver (1=APOPT,3=IPOPT)
m.solve(dispatch=False) # solve locally (remote=False)
print('y: ' + str(y.value)) # print variable value

```

y: [1.0]

### 4.9.3 Solve Linear Equations

$$3x + 2y = 1$$

$$x + 2y = 0$$

```
m = GEKKO()          # create GEKKO model
x = m.Var()         # define new variable, default=0
y = m.Var()         # define new variable, default=0
m.Equations([3*x+2*y==1, x+2*y==0]) # equations
m.solve(dis=False)  # solve
print(x.value,y.value) # print solution
```

[0.5] [-0.25]

### 4.9.4 Solve Nonlinear Equations

$$x + 2y = 0$$

$$x^2 + y^2 = 1$$

```
m = GEKKO()          # create GEKKO model
x = m.Var(value=0)   # define new variable, initial value=0
y = m.Var(value=1)   # define new variable, initial value=1
m.Equations([x + 2*y==0, x**2+y**2==1]) # equations
m.solve(dis=False)   # solve
print([x.value[0],y.value[0]]) # print solution
```

[-0.8944272, 0.4472136]

### 4.9.5 Interpolation with Cubic Spline

```
import numpy as np
import matplotlib.pyplot as plt

xm = np.array([0,1,2,3,4,5])
ym = np.array([0.1,0.2,0.3,0.5,1.0,0.9])

m = GEKKO()          # create GEKKO model
m.options.IMODE = 2  # solution mode
x = m.Param(value=np.linspace(-1,6)) # prediction points
y = m.Var()         # prediction results
m.cspline(x, y, xm, ym) # cubic spline
m.solve(dis=False)   # solve

# create plot
plt.plot(xm,ym,'bo')
plt.plot(x.value,y.value,'r--',label='cubic spline')
plt.legend(loc='best')
```

### 4.9.6 Linear and Polynomial Regression

```

import numpy as np
import matplotlib.pyplot as plt

xm = np.array([0,1,2,3,4,5])
ym = np.array([0.1,0.2,0.3,0.5,0.8,2.0])

#### Solution
m = GEKKO()
m.options.IMODE=2
# coefficients
c = [m.FV(value=0) for i in range(4)]
x = m.Param(value=xm)
y = m.CV(value=ym)
y.FSTATUS = 1
# polynomial model
m.Equation(y==c[0]+c[1]*x+c[2]*x**2+c[3]*x**3)

# linear regression
c[0].STATUS=1
c[1].STATUS=1
m.solve(dispatch=False)
p1 = [c[1].value[0],c[0].value[0]]

# quadratic
c[2].STATUS=1
m.solve(dispatch=False)
p2 = [c[2].value[0],c[1].value[0],c[0].value[0]]

# cubic
c[3].STATUS=1
m.solve(dispatch=False)
p3 = [c[3].value[0],c[2].value[0],c[1].value[0],c[0].value[0]]

# plot fit
plt.plot(xm,ym,'ko',markersize=10)
xp = np.linspace(0,5,100)
plt.plot(xp,np.polyval(p1,xp),'b--',linewidth=2)
plt.plot(xp,np.polyval(p2,xp),'r--',linewidth=3)
plt.plot(xp,np.polyval(p3,xp),'g:',linewidth=2)
plt.legend(['Data','Linear','Quadratic','Cubic'],loc='best')
plt.xlabel('x')
plt.ylabel('y')

```

## 4.9.7 Nonlinear Regression

```

import numpy as np
import matplotlib.pyplot as plt

# measurements
xm = np.array([0,1,2,3,4,5])
ym = np.array([0.1,0.2,0.3,0.5,0.8,2.0])

# GEKKO model
m = GEKKO()

```

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```

# parameters
x = m.Param(value=xm)
a = m.FV()
a.STATUS=1

# variables
y = m.CV(value=ym)
y.FSTATUS=1

# regression equation
m.Equation(y==0.1*m.exp(a*x))

# regression mode
m.options.IMODE = 2

# optimize
m.solve(dispatch=False)

# print parameters
print('Optimized, a = ' + str(a.value[0]))

plt.plot(xm, ym, 'bo')
plt.plot(xm, y.value, 'r-')

```

## 4.9.8 Solve Differential Equation(s)

Solve the following differential equation with initial condition  $y(0) = 5$ :

$$k \frac{dy}{dt} = ty$$

where  $k = 10$ . The solution of  $y(t)$  should be reported from an initial time 0 to final time 20. Create a plot of the result for  $y(t)$  versus  $t$ :

```

from gekko import GEKKO
import numpy as np
import matplotlib.pyplot as plt

m = GEKKO()
m.time = np.linspace(0, 20, 100)
k = 10
y = m.Var(value=5.0)
t = m.Param(value=m.time)
m.Equation(k*y.dt() == -t*y)
m.options.IMODE = 4
m.solve(dispatch=False)

plt.plot(m.time, y.value)
plt.xlabel('time')
plt.ylabel('y')

```

## 4.9.9 Mixed Integer Nonlinear Programming

```

from gekko import GEKKO
m = GEKKO() # Initialize gekko
m.options.SOLVER=1 # APOPT is an MINLP solver

# optional solver settings with APOPT
m.solver_options = ['minlp_maximum_iterations 500', \
                    # minlp iterations with integer solution
                    'minlp_max_iter_with_int_sol 10', \
                    # treat minlp as nlp
                    'minlp_as_nlp 0', \
                    # nlp sub-problem max iterations
                    'nlp_maximum_iterations 50', \
                    # 1 = depth first, 2 = breadth first
                    'minlp_branch_method 1', \
                    # maximum deviation from whole number
                    'minlp_integer_tol 0.05', \
                    # convergence tolerance
                    'minlp_gap_tol 0.01']

# Initialize variables
x1 = m.Var(value=1, lb=1, ub=5)
x2 = m.Var(value=5, lb=1, ub=5)
# Integer constraints for x3 and x4
x3 = m.Var(value=5, lb=1, ub=5, integer=True)
x4 = m.Var(value=1, lb=1, ub=5, integer=True)
# Equations
m.Equation(x1*x2*x3*x4>=25)
m.Equation(x1**2+x2**2+x3**2+x4**2==40)
m.Obj(x1*x4*(x1+x2+x3)+x3) # Objective
m.solve(dispatch=False) # Solve
print('Results')
print('x1: ' + str(x1.value))
print('x2: ' + str(x2.value))
print('x3: ' + str(x3.value))
print('x4: ' + str(x4.value))
print('Objective: ' + str(m.options.objfcnval))

```

Results x1: [1.358909] x2: [4.599279] x3: [4.0] x4: [1.0] Objective: 17.5322673

## 4.9.10 Moving Horizon Estimation

```

from gekko import GEKKO
import numpy as np
import matplotlib.pyplot as plt

# Estimator Model
m = GEKKO()
m.time = p.time
# Parameters
m.u = m.MV(value=u_meas) #input
m.K = m.FV(value=1, lb=1, ub=3) # gain
m.tau = m.FV(value=5, lb=1, ub=10) # time constant
# Variables
m.x = m.SV() #state variable

```

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```
m.y = m.CV(value=y_meas) #measurement
# Equations
m.Equations([m.tau * m.x.dt() == -m.x + m.u,
             m.y == m.K * m.x])
# Options
m.options.IMODE = 5 #MHE
m.options.EV_TYPE = 1
# STATUS = 0, optimizer doesn't adjust value
# STATUS = 1, optimizer can adjust
m.u.STATUS = 0
m.K.STATUS = 1
m.tau.STATUS = 1
m.y.STATUS = 1
# FSTATUS = 0, no measurement
# FSTATUS = 1, measurement used to update model
m.u.FSTATUS = 1
m.K.FSTATUS = 0
m.tau.FSTATUS = 0
m.y.FSTATUS = 1
# DMAX = maximum movement each cycle
m.K.DMAX = 2.0
m.tau.DMAX = 4.0
# MEAS_GAP = dead-band for measurement / model mismatch
m.y.MEAS_GAP = 0.25

# solve
m.solve(dispatch=False)

# Plot results
plt.subplot(2,1,1)
plt.plot(m.time,u_meas,'b:',label='Input (u) meas')
plt.legend()
plt.subplot(2,1,2)
plt.plot(m.time,y_meas,'gx',label='Output (y) meas')
plt.plot(p.time,p.y.value,'k-',label='Output (y) actual')
plt.plot(m.time,m.y.value,'r--',label='Output (y) estimated')
plt.legend()
plt.show()
```

## 4.9.11 Model Predictive Control

```
from gekko import GEKKO
import numpy as np
import matplotlib.pyplot as plt

m = GEKKO()
m.time = np.linspace(0,20,41)

# Parameters
mass = 500
b = m.Param(value=50)
K = m.Param(value=0.8)

# Manipulated variable
p = m.MV(value=0, lb=0, ub=100)
```

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```

p.STATUS = 1 # allow optimizer to change
p.DCOST = 0.1 # smooth out gas pedal movement
p.DMAX = 20 # slow down change of gas pedal

# Controlled Variable
v = m.CV(value=0)
v.STATUS = 1 # add the SP to the objective
m.options.CV_TYPE = 2 # squared error
v.SP = 40 # set point
v.TR_INIT = 1 # set point trajectory
v.TAU = 5 # time constant of trajectory

# Process model
m.Equation(mass*v.dt() == -v*b + K*b*p)

m.options.IMODE = 6 # control
m.solve(dis=False)

# get additional solution information
import json
with open(m.path+'//results.json') as f:
    results = json.load(f)

plt.figure()
plt.subplot(2,1,1)
plt.plot(m.time,p.value,'b-',label='MV Optimized')
plt.legend()
plt.ylabel('Input')
plt.subplot(2,1,2)
plt.plot(m.time,results['v1.tr'],'k-',label='Reference Trajectory')
plt.plot(m.time,v.value,'r--',label='CV Response')
plt.ylabel('Output')
plt.xlabel('Time')
plt.legend(loc='best')
plt.show()

```

## 4.9.12 Additional Examples

```

* `18 Applications with Python GEKKO <https://apmonitor.com/wiki/index.php/Main/GekkoPythonOptimization>`_
↪GekkoPythonOptimization>`_
* `Dynamic Optimization Course (see Homework Solutions) <http://apmonitor.com/do/index.php/Main/InvertedPendulum>`_
↪index.php/Main/InvertedPendulum>`_
* `GEKKO Search on APMonitor Documentation <http://apmonitor.com/wiki/index.php?n=Main.HomePage&action=search&q=gekko>`_
↪n=Main.HomePage&action=search&q=gekko>`_
* `GEKKO (optimization software) on Wikipedia <https://en.wikipedia.org/wiki/Gekko\_\(optimization\_software\)>`_
↪(optimization_software)>`_
* `GEKKO Journal Article <https://www.mdpi.com/2227-9717/6/8/106>`_
↪https://www.mdpi.com/2227-9717/6/8/106>`_
* `GEKKO Webinar to the AIChE CAST Division <https://github.com/loganbeal/CAST\_GEKKO\_webinar>`_
↪webinar>`_

```

## 4.10 Support

### 4.10.1 Bugs

GEKKO is in its early stages and still under active development. If you identify a bug in the package, please submit an issue on [GitHub](#).

If you would like to contribute to GEKKO development, please make pull requests on the [GitHub repo](#).

### 4.10.2 Questions

Further clarification regarding the APMonitor functionality on the back end of GEKKO, please join the [APMonitor User Group](#).

### 4.10.3 Advanced Debugging

The files read/written by GEKKO and APMonitor are in the folder indicated in *m.\_path*. Information on debugging these files is available on [APMonitor](#).

## CHAPTER 5

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### Overview of GEKKO

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