NLPImplicitSolver

August 4, 2024

1 NLPImplicitSolver

[1]:
```python
from casadi import *
from numpy import *
from pylab import *
```

We will investigate the working of rootfinder with the help of the parametrically exited Duffing equation.

$\ddot{u} + \dot{u} - \epsilon(2\mu\dot{u} + \alpha u^3 + 2ku\cos(\Omega t))$ with $\Omega = 2 + \epsilon\sigma$. \

The first order solution is $u(t) = a\cos(\frac{1}{2}\Omega t - \frac{1}{2}\gamma)$ with the modulation equations: \ $\frac{da}{d\epsilon t} = -\left[\mu a + \frac{1}{2}ka\sin\gamma\right]$ \ $a\frac{d\gamma}{d\epsilon t} = -\left[-\sigma a + \frac{3}{4}\alpha a^3 + ka\cos\gamma\right]$ \

We seek the stationair solution to these modulation equations.

Parameters

```
[2]: eps   = SX.sym("eps")
     mu    = SX.sym("mu")
     alpha = SX.sym("alpha")
     k     = SX.sym("k")
     sigma = SX.sym("sigma")
     params = [eps,mu,alpha,k,sigma]
```

Variables

```
[3]: a     = SX.sym("a")
     gamma = SX.sym("gamma")
```

Equations

```
[4]: res0 = mu*a+1.0/2*k*a*sin(gamma)
     res1 = -sigma * a + 3.0/4*alpha*a**3+k*a*cos(gamma)
```

Numerical values

```
[5]: sigma_  = 0.1
     alpha_  = 0.1
     k_      = 0.2
     params_ = [0.1,0.1,alpha_,k_,sigma_]
```

We create a NLPImplicitSolver instance

```
[6]: f=Function("f", [vertcat(a, gamma), vertcat(*params)], [vertcat(res0, res1)])
     opts = {}
     opts["nlpsol"] = "ipopt"
     opts["nlpsol_options"] = {"ipopt.tol":1e-14}
     s=rootfinder("s", "nlpsol", f, opts)
```

Initialize $[a, \gamma]$ with a guess and solve

```
[7]: x_ = s([1,-1], params_)
     print("Solution = ", x_)
```

```
******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear optimization.
 Ipopt is released as open source code under the Eclipse Public License (EPL).
         For more information visit https://github.com/coin-or/Ipopt
******************************************************************************

This is Ipopt version 3.14.11, running with linear solver MUMPS 5.4.1.

Number of nonzeros in equality constraint Jacobian…:        4
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian…:        3
```

```
Total number of variables…:        2
                     variables with only lower bounds:        0
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints…:        2
Total number of inequality constraints…:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
   0  0.0000000e+00 8.31e-02 0.00e+00  -1.0 0.00e+00    -  0.00e+00 0.00e+00   0
   1  0.0000000e+00 1.23e-02 0.00e+00  -2.5 2.40e-01    -  1.00e+00 1.00e+00h  1
   2  0.0000000e+00 2.02e-03 0.00e+00  -3.8 2.00e-01    -  1.00e+00 1.00e+00h  1
   3  0.0000000e+00 1.28e-03 0.00e+00  -3.8 1.15e-01    -  1.00e+00 1.00e+00h  1
   4  0.0000000e+00 4.42e-05 0.00e+00  -5.7 2.96e-02    -  1.00e+00 1.00e+00h  1
   5  0.0000000e+00 2.30e-05 0.00e+00  -5.7 1.68e-02    -  1.00e+00 1.00e+00h  1
   6  0.0000000e+00 5.32e-06 0.00e+00  -5.7 8.03e-03    -  1.00e+00 1.00e+00h  1
   7  0.0000000e+00 1.34e-06 0.00e+00  -8.6 3.98e-03    -  1.00e+00 1.00e+00h  1
   8  0.0000000e+00 3.35e-07 0.00e+00  -8.6 1.98e-03    -  1.00e+00 1.00e+00h  1
   9  0.0000000e+00 8.38e-08 0.00e+00  -8.6 9.87e-04    -  1.00e+00 1.00e+00h  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
  10  0.0000000e+00 2.10e-08 0.00e+00  -8.6 4.93e-04    -  1.00e+00 1.00e+00h  1
  11  0.0000000e+00 5.24e-09 0.00e+00 -12.9 2.46e-04    -  1.00e+00 1.00e+00h  1
  12  0.0000000e+00 1.31e-09 0.00e+00 -12.9 1.23e-04    -  1.00e+00 1.00e+00h  1
  13  0.0000000e+00 3.28e-10 0.00e+00 -12.9 6.15e-05    -  1.00e+00 1.00e+00h  1
  14  0.0000000e+00 8.19e-11 0.00e+00 -12.9 3.08e-05    -  1.00e+00 1.00e+00h  1
  15  0.0000000e+00 2.05e-11 0.00e+00 -12.9 1.54e-05    -  1.00e+00 1.00e+00h  1
  16  0.0000000e+00 5.12e-12 0.00e+00 -12.9 7.69e-06    -  1.00e+00 1.00e+00h  1
  17  0.0000000e+00 1.28e-12 0.00e+00 -12.9 3.84e-06    -  1.00e+00 1.00e+00h  1
  18  0.0000000e+00 3.20e-13 0.00e+00 -12.9 1.92e-06    -  1.00e+00 1.00e+00h  1
  19  0.0000000e+00 8.00e-14 0.00e+00 -15.0 9.61e-07    -  1.00e+00 1.00e+00h  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
  20  0.0000000e+00 2.00e-14 0.00e+00 -15.0 4.80e-07    -  1.00e+00 1.00e+00h  1
  21  0.0000000e+00 5.04e-15 0.00e+00 -15.0 2.40e-07    -  1.00e+00 1.00e+00h  1

Number of Iterations…: 21

                                   (scaled)                 (unscaled)
Objective…:   0.0000000000000000e+00    0.0000000000000000e+00
Dual infeasibility…:   0.0000000000000000e+00    0.0000000000000000e+00
Constraint violation…:   5.0404780683255265e-15    5.0404780683255265e-15
Variable bound violation:   0.0000000000000000e+00    0.0000000000000000e+00
Complementarity…:   0.0000000000000000e+00    0.0000000000000000e+00
Overall NLP error…:   5.0404780683255265e-15    5.0404780683255265e-15
```

```
Number of objective function evaluations             = 22
Number of objective gradient evaluations             = 22
Number of equality constraint evaluations            = 22
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 22
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 21
Total seconds in IPOPT                               = 0.029

EXIT: Optimal Solution Found.
      nlpsol  :   t_proc      (avg)   t_wall      (avg)    n_eval
       nlp_f  | 181.00us (  8.23us)  43.10us (  1.96us)        22
       nlp_g  | 456.00us ( 20.73us) 105.61us (  4.80us)        22
  nlp_grad_f  | 264.00us ( 11.48us)  59.72us (  2.60us)        23
  nlp_hess_l  | 591.00us ( 28.14us) 144.04us (  6.86us)        21
   nlp_jac_g  | 526.00us ( 22.87us) 130.33us (  5.67us)        23
       total  | 119.88ms (119.88ms)  29.97ms ( 29.97ms)         1
Solution =  [1.1547, -1.5708]
```

Compare with the analytic solution:

[8]:
```
x = [sqrt(4.0/3*sigma_/alpha_),-0.5*pi]
print("Reference solution = ", x)
```

```
Reference solution =  [1.1547005383792515, -1.5707963267948966]
```

We show that the residual is indeed (close to) zero

[9]:
```
residual = f(x_, params_)
print("residual = ", residual)
```

```
residual =  [2.498e-15, 5.04048e-15]
```

[10]:
```
for i in range(1):
  assert(abs(x_[i]-x[i])<1e-6)
```

Solver statistics

[11]:
```
print(s.stats())
```

```
{'n_call_jac_f_z': 0, 'nlpsol': {'iter_count': 21, 'iterations': {'alpha_du':
[0.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0,
1.0, 1.0, 1.0, 1.0, 1.0, 1.0], 'alpha_pr': [0.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0,
1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0],
'd_norm': [0.0, 0.23960592290193847, 0.2002776648351239, 0.11462838134468271,
0.029608423804759445, 0.016763794276380726, 0.008032525850076699,
0.003977508980797005, 0.0019782511377219327, 0.000986563314767321,
0.0004926468651346938, 0.0002461654667430133, 0.00012304333360478557,
6.151182779221677e-05, 3.075345789240383e-05, 1.5376112167388994e-05,
7.687910912446485e-06, 3.8438997812749356e-06, 1.92194207223915e-06,
```

9.61008195593693e-07, 4.804365673649445e-07, 2.404509433067261e-07], 'inf_du': [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0], 'inf_pr': [0.08306046117362796, 0.012290452768353485, 0.0020204300142100742, 0.0012794397549934066, 4.421852776412272e-05, 2.300330418598907e-05, 5.321988750748349e-06, 1.3390883536304509e-06, 3.3506843297604477e-07, 8.381216439051482e-08, 2.09588221506264e-08, 5.24043895038358e-09, 1.310202083785794e-09, 3.2756211715529815e-10, 8.189201858746866e-11, 2.047313311593076e-11, 5.118331222212175e-12, 1.2796006133619685e-12, 3.1984623222892154e-13, 8.003960858313451e-14, 1.9956499544108217e-14, 5.0404780683255265e-15], 'mu': [0.1, 0.002828427124746191, 0.00015042412372345582, 0.00015042412372345582, 1.8449144625279508e-06, 1.8449144625279508e-06, 1.8449144625279508e-06, 2.5059035596800618e-09, 2.5059035596800618e-09, 2.5059035596800618e-09, 2.5059035596800618e-09, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 1.2544302826334687e-13, 9.090909090909092e-16, 9.090909090909092e-16, 9.090909090909092e-16], 'obj': [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0], 'regularization_size': [0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0]}, 'n_call_callback_fun': 0, 'n_call_nlp_f': 22, 'n_call_nlp_g': 22, 'n_call_nlp_grad': 0, 'n_call_nlp_grad_f': 23, 'n_call_nlp_hess_l': 21, 'n_call_nlp_jac_g': 23, 'n_call_total': 1, 'return_status': 'Solve_Succeeded', 'success': True, 't_proc_callback_fun': 0.0, 't_proc_nlp_f': 0.00018100000000000004, 't_proc_nlp_g': 0.000456, 't_proc_nlp_grad': 0.0, 't_proc_nlp_grad_f': 0.00026399999999999997, 't_proc_nlp_hess_l': 0.0005909999999999999, 't_proc_nlp_jac_g': 0.0005260000000000001, 't_proc_total': 0.119876, 't_wall_callback_fun': 0.0, 't_wall_nlp_f': 4.309599999999999e-05, 't_wall_nlp_g': 0.00010560900000000003, 't_wall_nlp_grad': 0.0, 't_wall_nlp_grad_f': 5.9724999999999995e-05, 't_wall_nlp_hess_l': 0.00014403900000000002, 't_wall_nlp_jac_g': 0.000130331, 't_wall_total': 0.029973671, 'unified_return_status': 'SOLVER_RET_UNKNOWN'}, 'success': True, 't_proc_jac_f_z': 0.0, 't_wall_jac_f_z': 0.0, 'unified_return_status': 'SOLVER_RET_UNKNOWN'}