Rock drilling efficiency revisited

Assessment of energy radiated to the rock halfspace

Summary of results

Summary of previous results

Rigid foundation instead of rock is considered

3D finite element computation compared with 1D theory for three drilling technologies

Ability of elastic waves to transport energy

is used in percussive rock drilling to transmit energy through a drill rod to a drill bit which converts a substantial part of the wave energy into work when it crushes the rock.

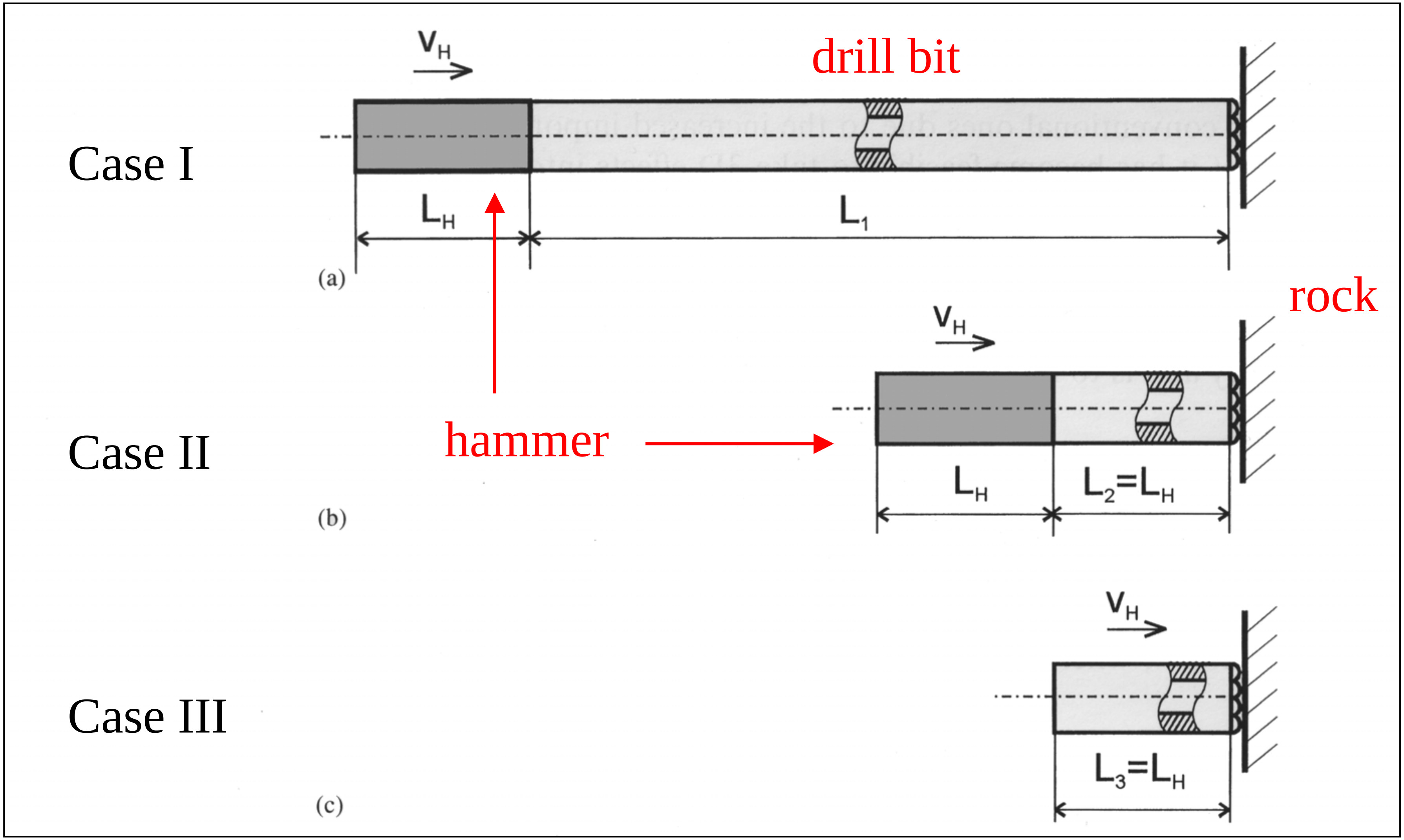
The efficiency of this process is the name of the game.

Rock drilling modes - technology

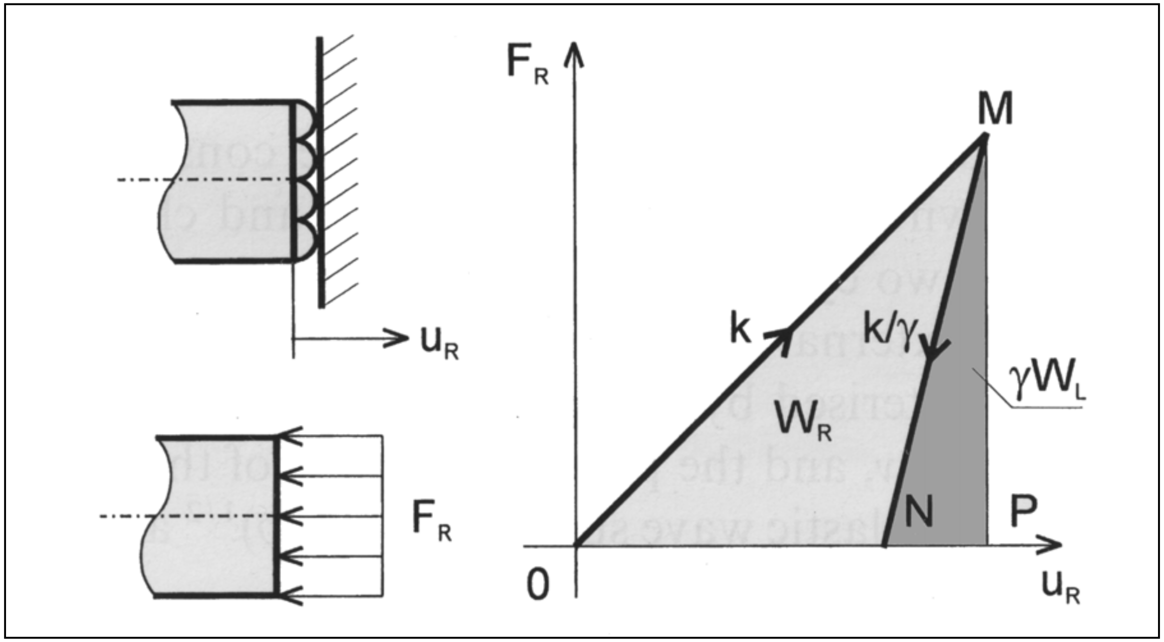
- a) Hammer drilling (Case I)
- b) Down-the-hole drilling (Case II)
- c) Churn drilling (Case III)

Rock drilling modes and tuning parameter

$$\beta = \frac{k}{AE/(2L_H)}$$



Drill-bit rock modelling and efficiency



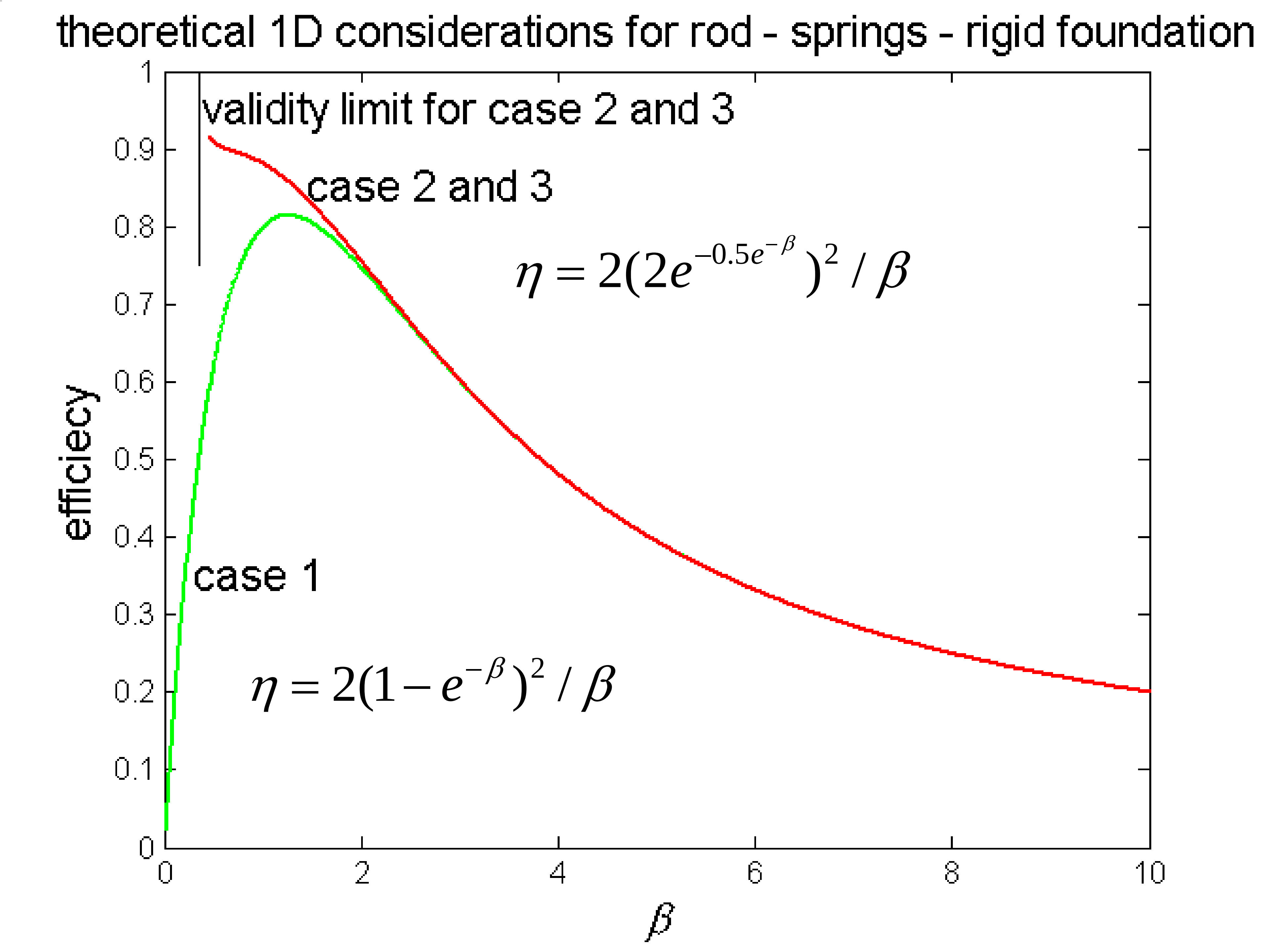
$$W_R = W_L - \gamma W_L$$

$$W_L = \int_0^M F_R \, du_R$$

$$W_{in} = \tfrac{1}{2} m_H v_H^2$$

$$\eta = \frac{W_{out}}{W_{in}} = \frac{W_R}{E_H^{kinetic}} = \frac{W_L(1-\gamma)}{W_{in}}$$

$$\eta^* = \frac{\eta}{1-\gamma} = \frac{W_L}{W_{in}}$$



theoretical 1D considerations for rod - springs - rigid foundation
validity limit for case 2 and 3
case 2 and 3
$\eta = 2(2e^{-0.5e^{-\beta}})^2 / \beta$
case 1
$\eta = 2(1-e^{-\beta})^2 / \beta$
efficiecy
β
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10

Impact modelling simplification

We assumed that the hammer hitting a rod induces at its impact face a sudden step wise increase of pressure which is uniformly distributed across the face and whose amplitude is given by Young's formula, valid for thin cylinders, i.e

$p_0 = E\, v_0 / c_0$ where, $c_0 = \sqrt{E / \rho}$

The loading pulse has a form of rectangular pulse, whose amplitude is p_0 and its length in time depends on the length of the hammer and is $timp = 2L_H / c_0$.

So instead of treating the actual impact between the hammer and the rod we solve a classical transient task with the prescribed loading in time by a suitable integration in time.

Energy computation

$$\eta^* = W_{\mathrm{out}} / W_{\mathrm{in}}$$

$$W_{\mathrm{in}} = \sum_{\mathrm{el}} \int_0^{timp} F_{\mathrm{in}}^{\mathrm{el}} v_{\mathrm{in}}^{\mathrm{el}} \,\mathrm{d}t = \sum_{\mathrm{el}} \int_0^{timp} F_{\mathrm{in}}^{\mathrm{el}} \,\mathrm{d}u_{\mathrm{in}}^{\mathrm{el}}$$

$$W_{\mathrm{out}} = \sum_{\mathrm{el}} \int_0^{tr} F_{\mathrm{rock}}^{\mathrm{el}} v_{\mathrm{rock}}^{\mathrm{el}} \,\mathrm{d}t = \sum_{\mathrm{el}} \int_0^{tr} F_{\mathrm{rock}}^{\mathrm{el}} \,\mathrm{d}u_{\mathrm{rock}}^{\mathrm{el}}$$

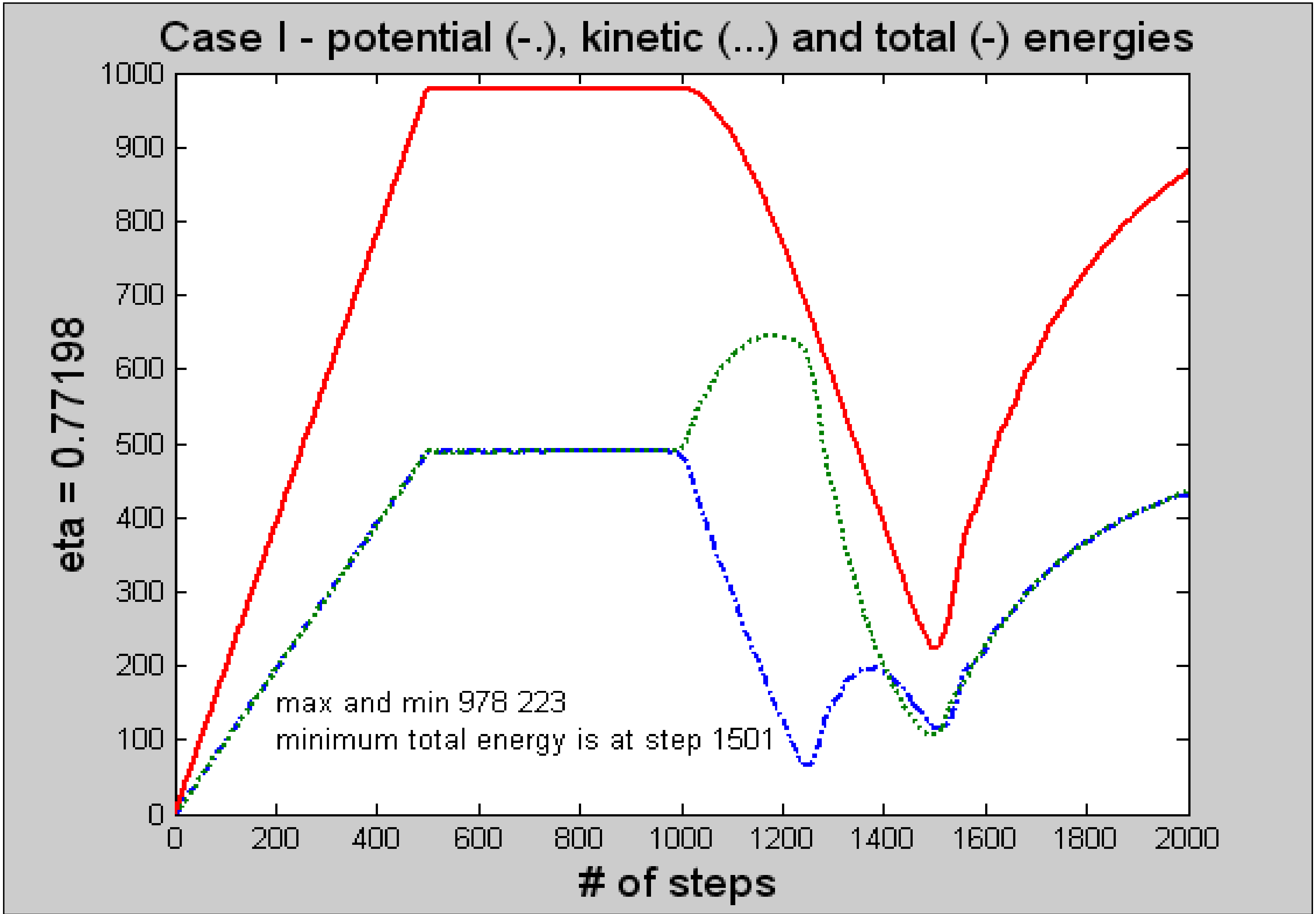
$$\eta^* = (E_{\mathrm{max}} - E_{\mathrm{min}}) / E_{\mathrm{max}}$$

$$E(t) = E_{\mathrm{k}}(t) + E_{\mathrm{p}}(t),$$

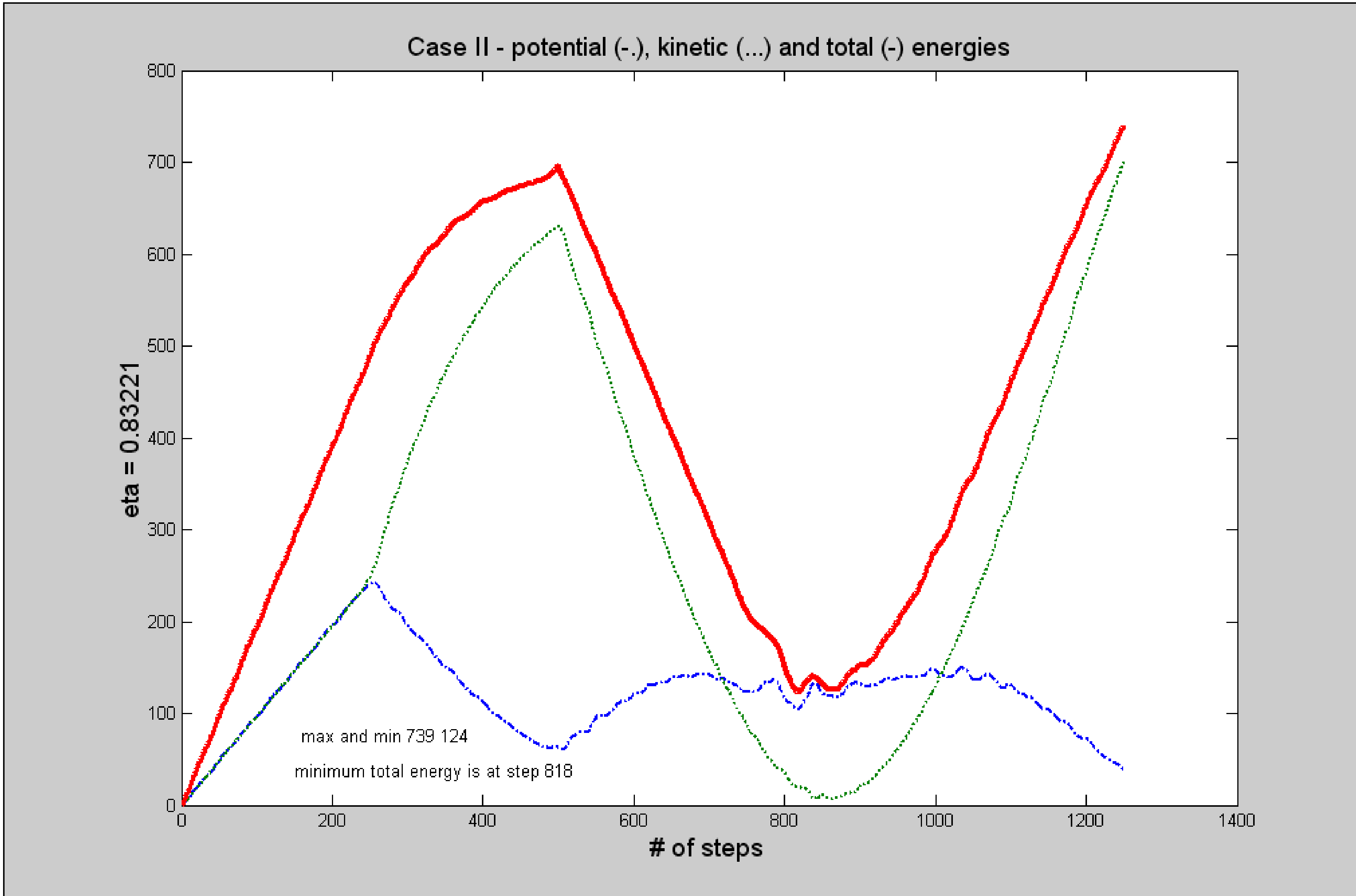
$$E_{\mathrm{k}}(t) = 0.5 * \mathbf{v}^{\mathrm{T}} \mathbf{M} \mathbf{v},$$

$$E_{\mathrm{p}}(t) = 0.5 * \mathbf{u}^{\mathrm{T}} \mathbf{K} \mathbf{u}$$

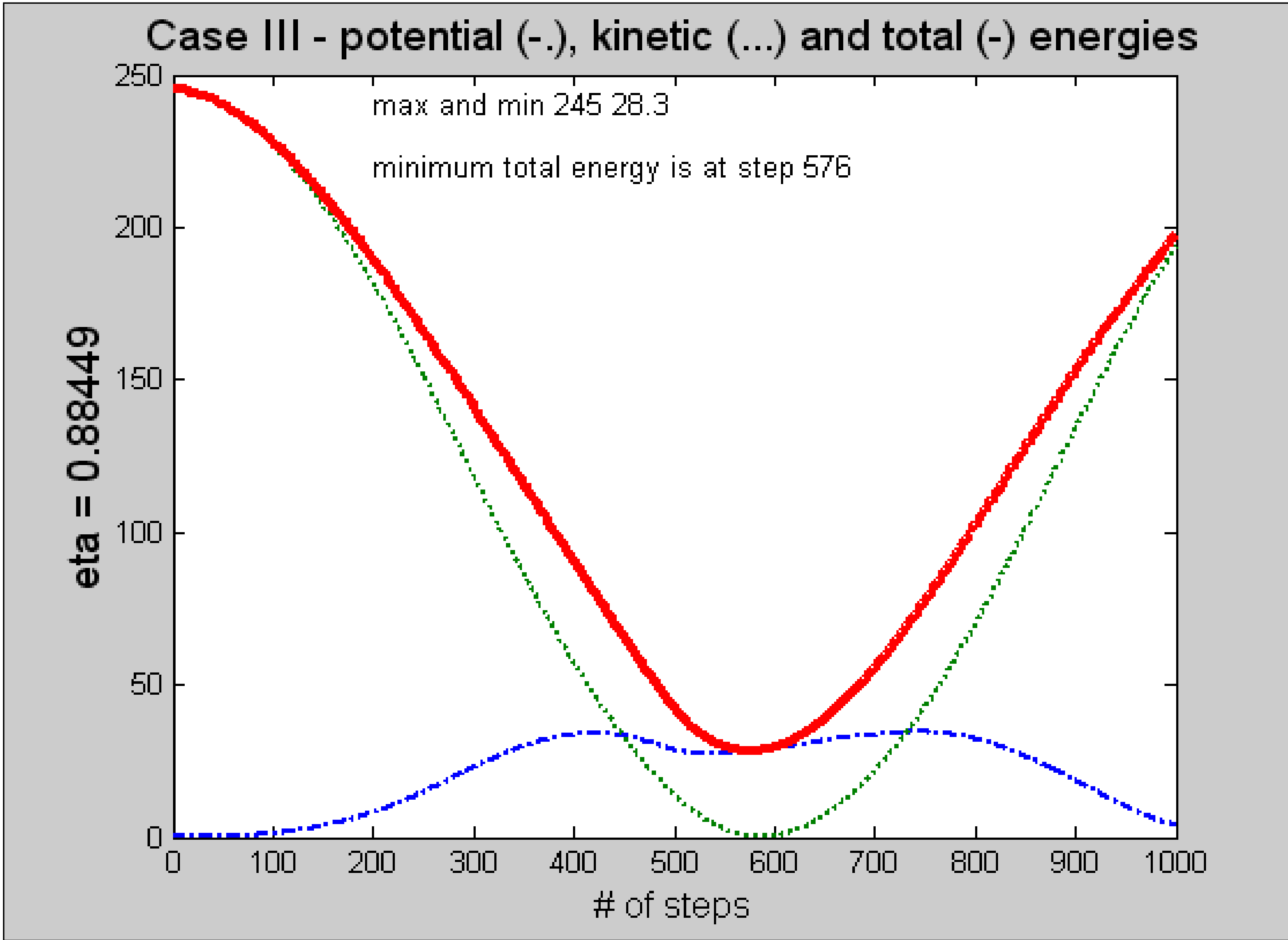
Typical time distribution of energies, case I



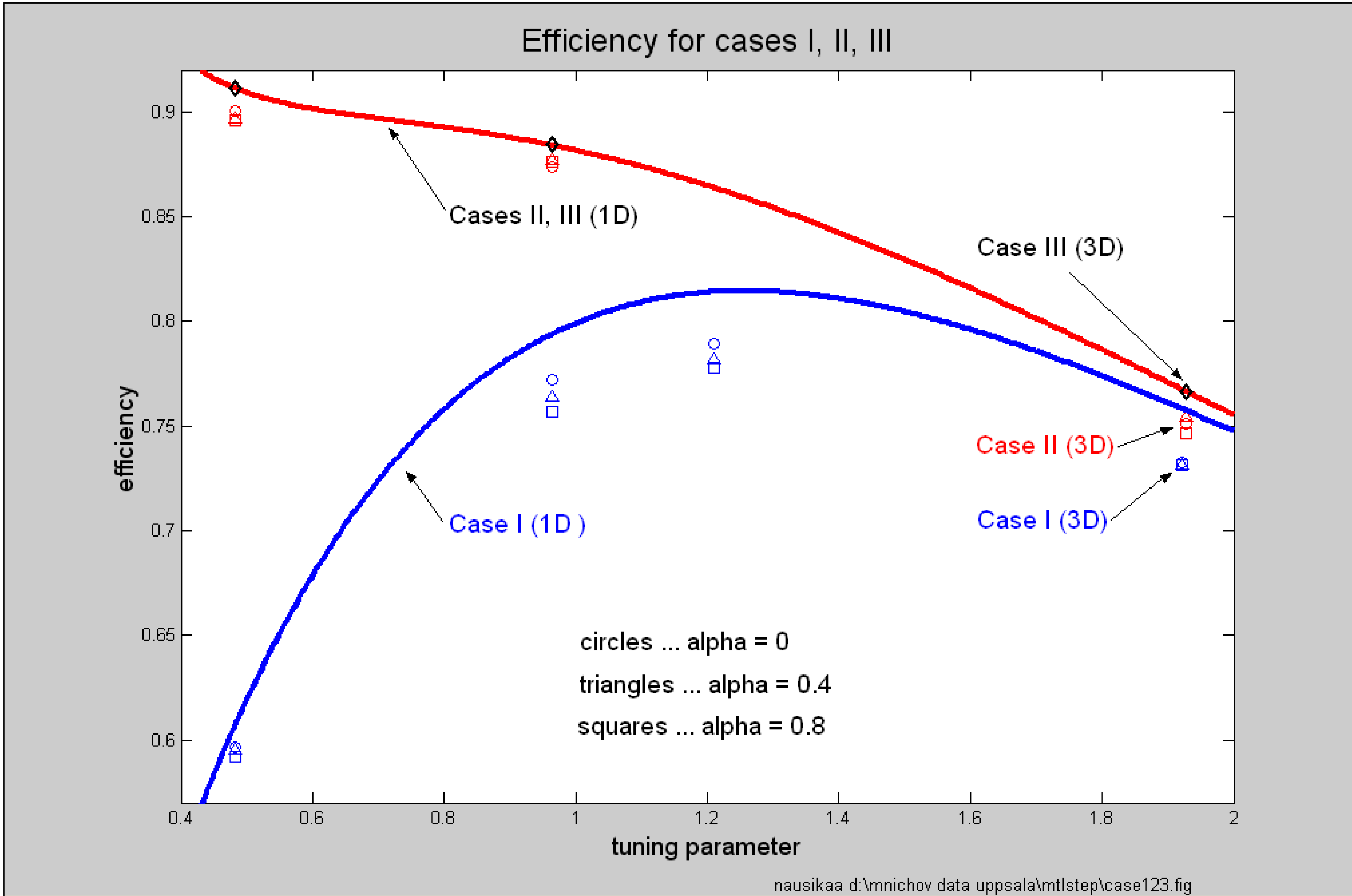
Typical time distribution of energies, case II



Typical time distribution of energies, case III



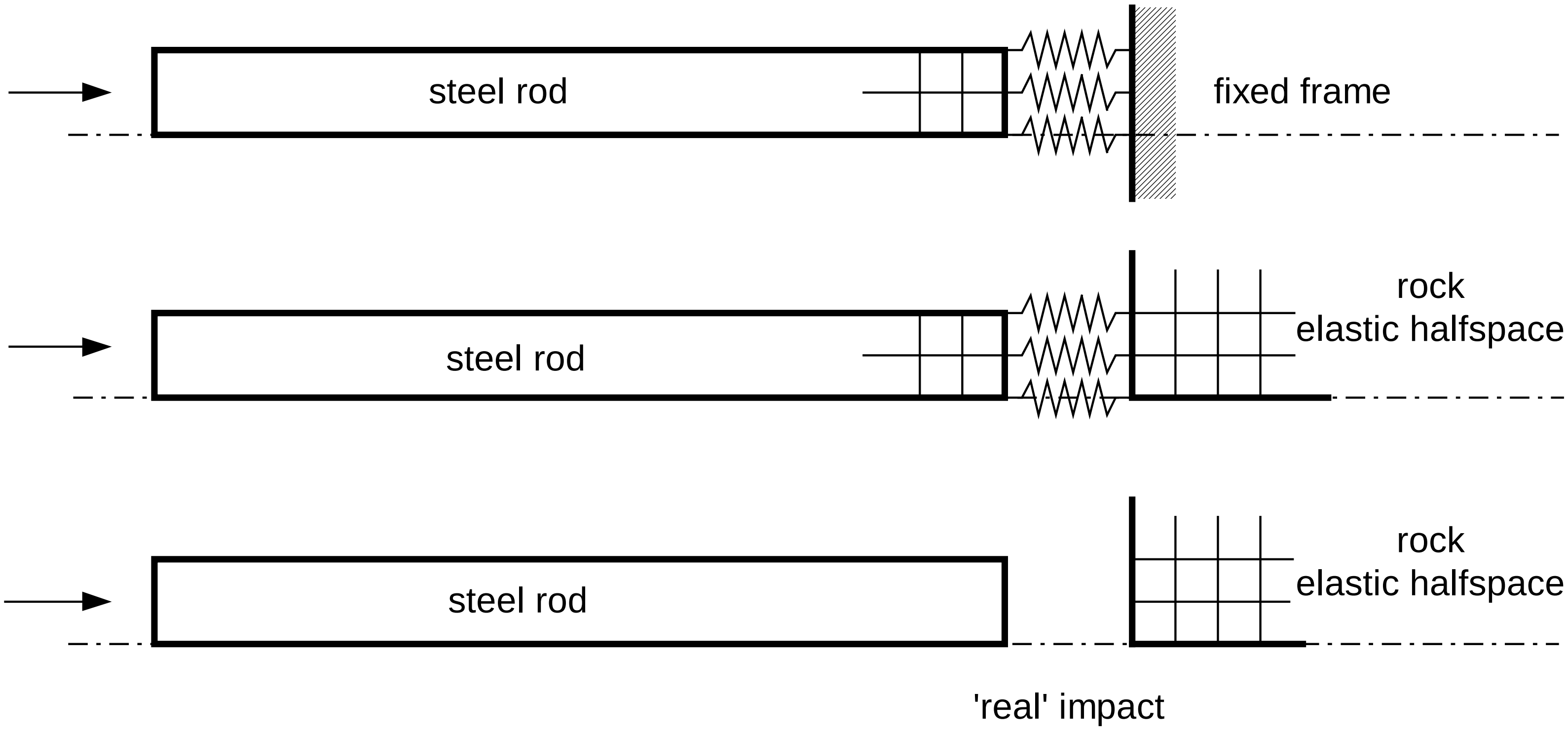
Efficiency vs. tuning – all three cases



Results for elastic rock response

Only churn drilling considered

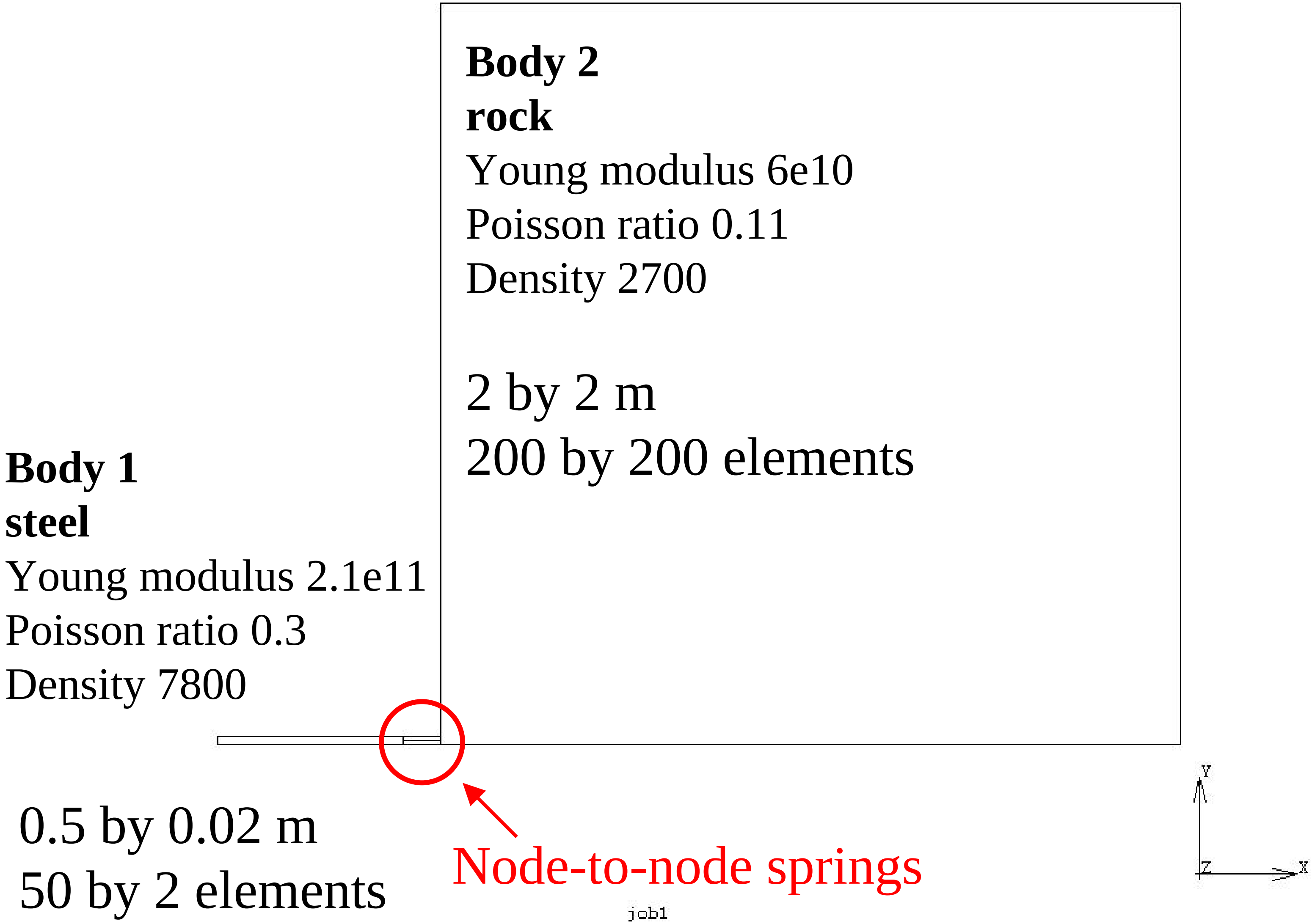
Churn drilling
Three cases were compared



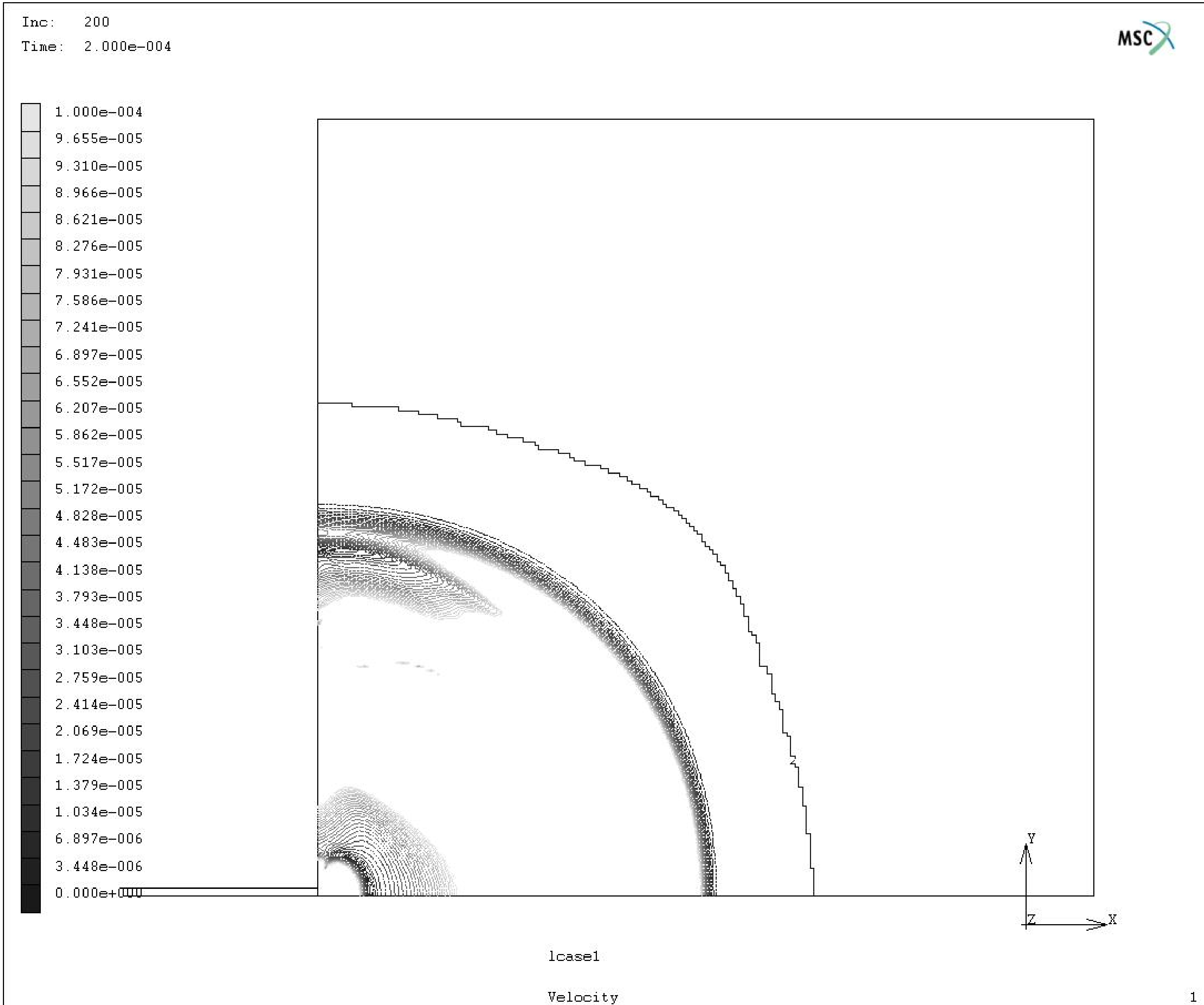
with 1D theory approach

Inc: 0
Time: 0.000e+000

Geometry and material



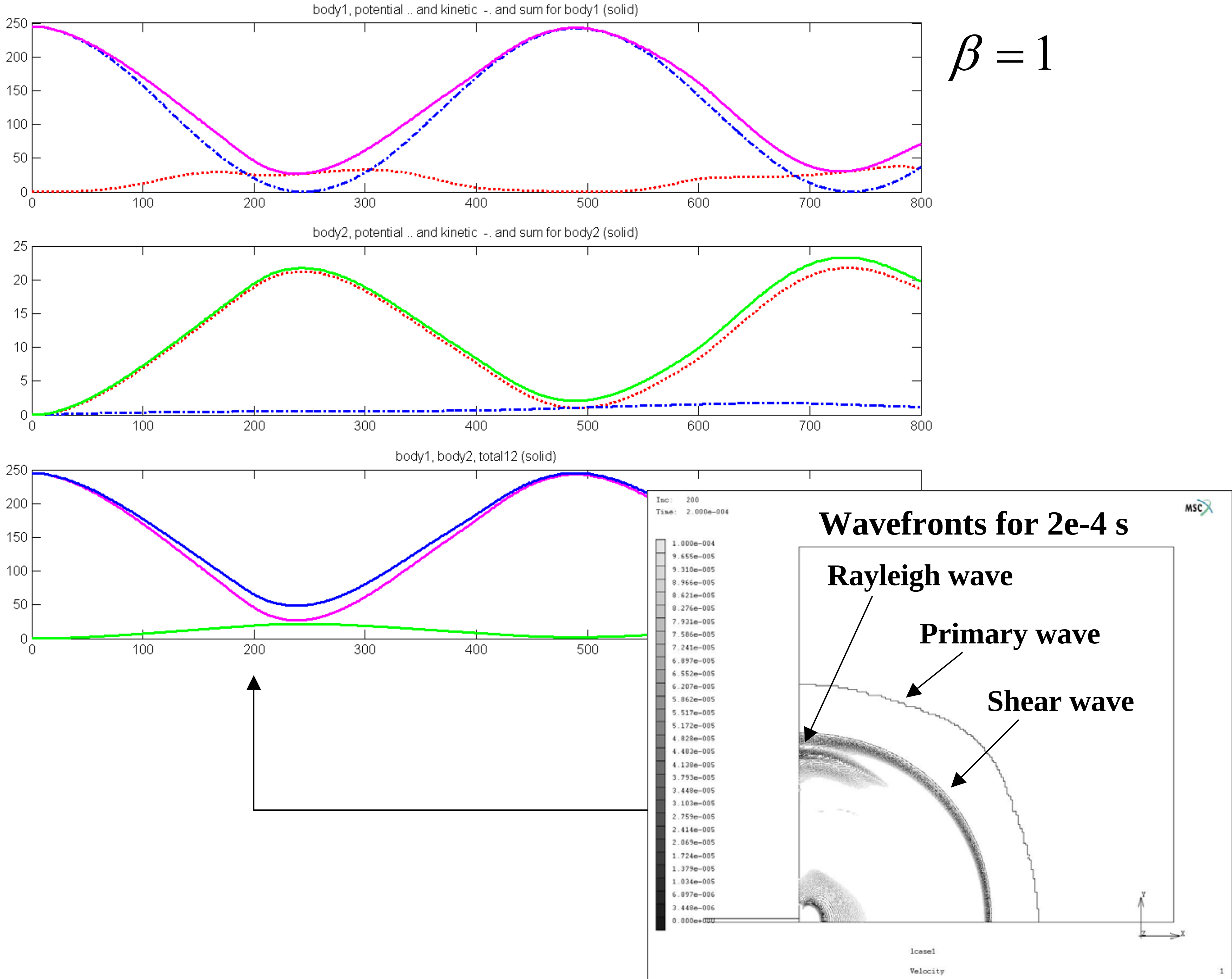
SI units used


Inc: 200
Time: 2.000e-004
1.000e-004
9.655e-005
9.310e-005
8.966e-005
8.621e-005
8.276e-005
7.931e-005
7.586e-005
7.241e-005
6.897e-005
6.552e-005
6.207e-005
5.862e-005
5.517e-005
5.172e-005
4.828e-005
4.483e-005
4.138e-005
3.793e-005
3.448e-005
3.103e-005
2.759e-005
2.414e-005
2.069e-005
1.724e-005
1.379e-005
1.034e-005
6.897e-006
3.448e-006
0.000e+000
Y
Z
X
lcase1
Velocity
1

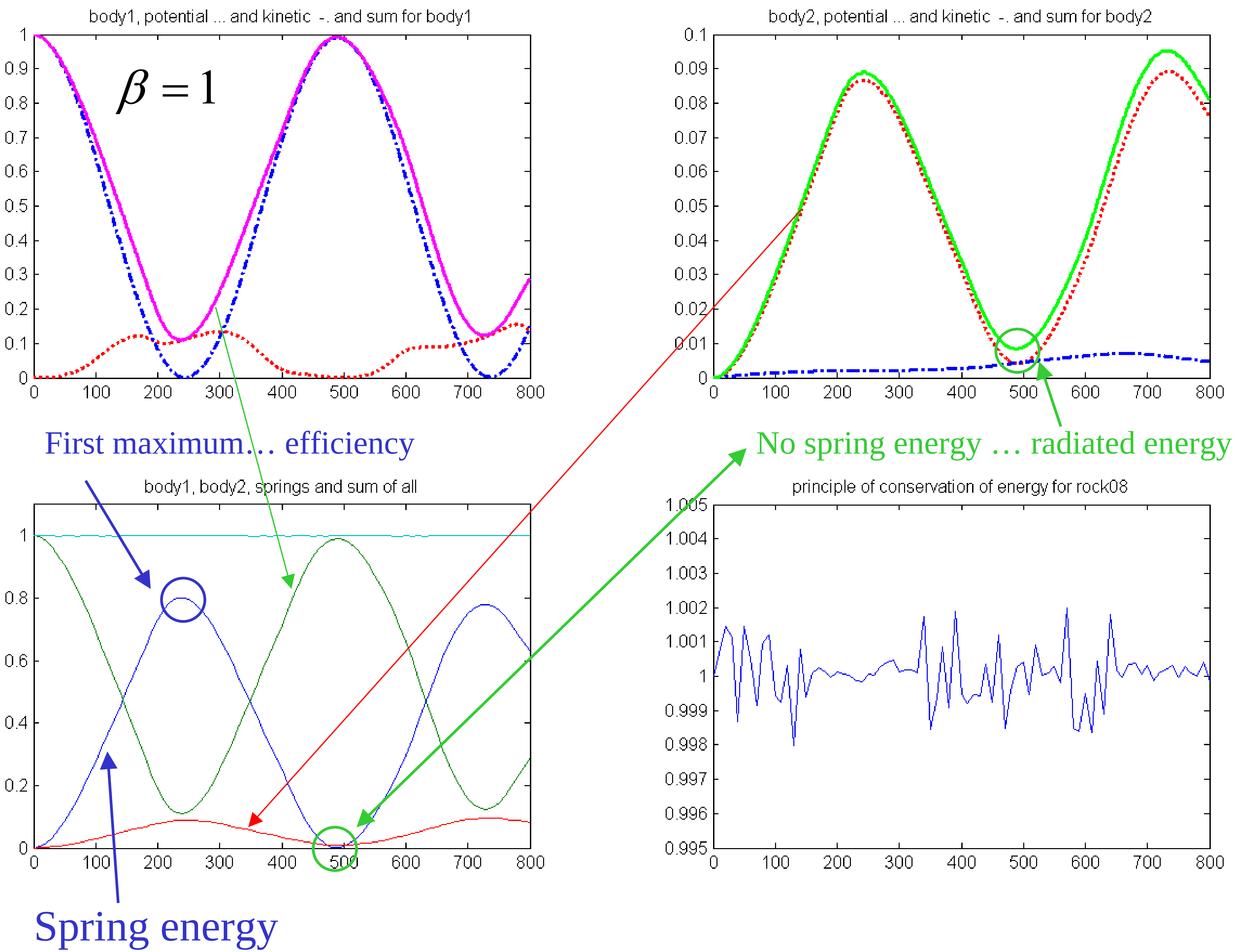
Material and wave speeds

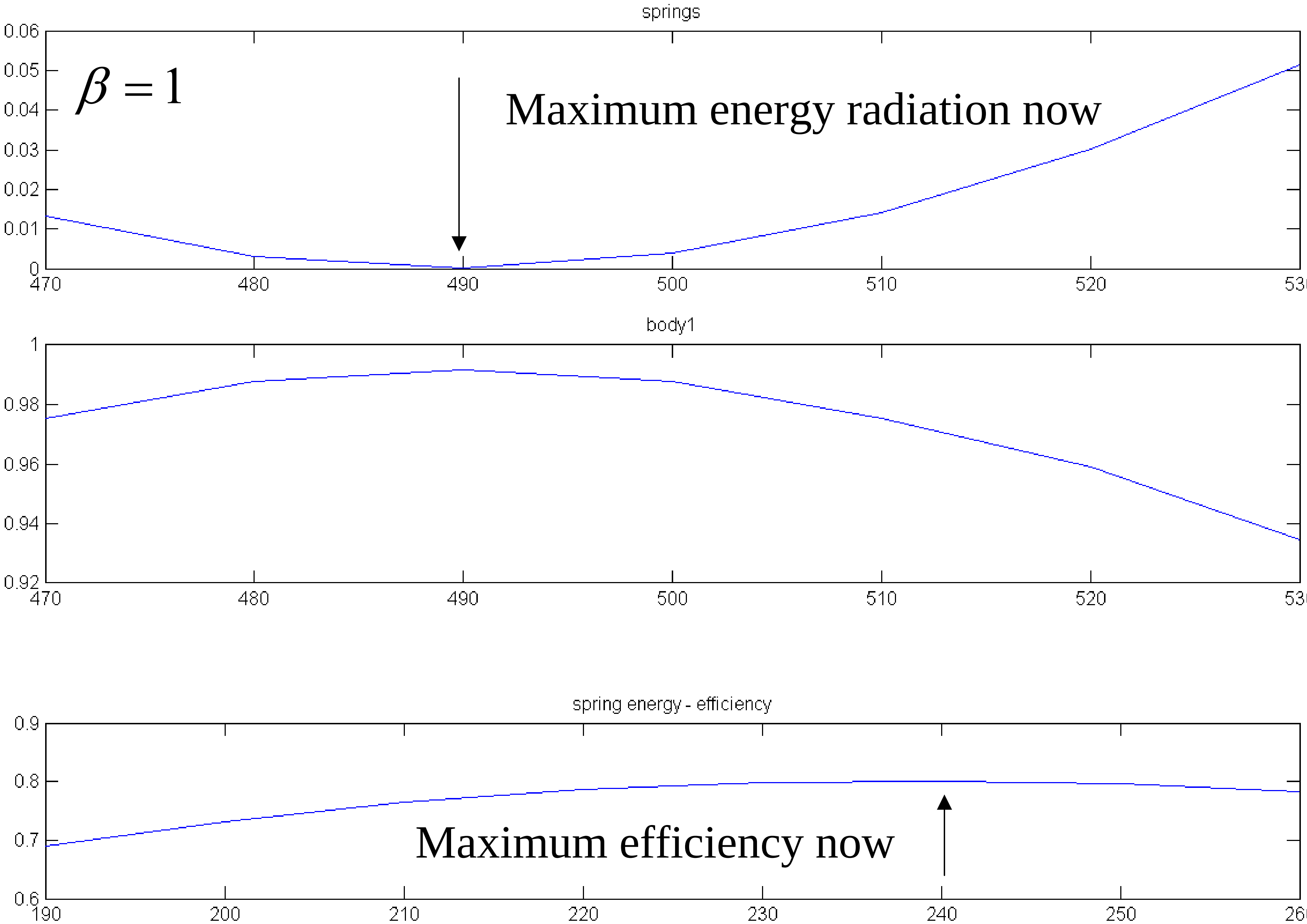
variable	rock	steel	units
Young	6e+010	2.1e+011	N/m^2
Poisson	0.11	0.3	[1]
density	2700	7800	kg/m^3
bar velocity	4714	5188.7	m/s
c1 velocity	4779.5	6020.2	m/s
shear velocity	3163.9	3217.9	m/s

$\beta = 1$

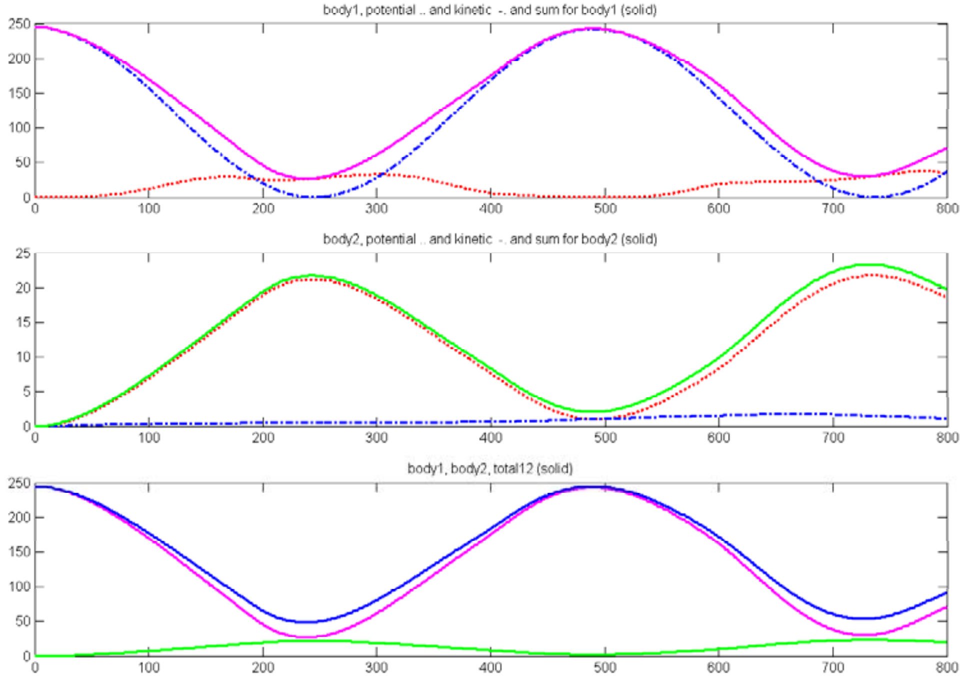


body1, potential .. and kinetic -. and sum for body1 (solid)
body2, potential .. and kinetic -. and sum for body2 (solid)
body1, body2, total12 (solid)
Wavefronts for 2e-4 s
Rayleigh wave
Primary wave
Shear wave
Inc: 200
Time: 2.000e-004
lcase1
Velocity

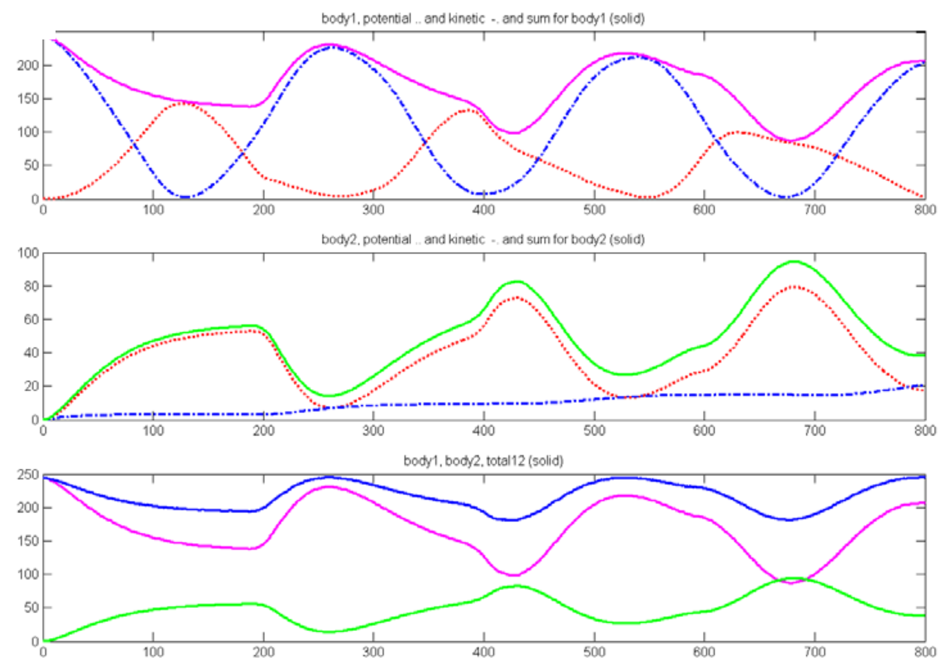

body1, potential ... and kinetic -. and sum for body1
$\beta = 1$
body2, potential ... and kinetic -. and sum for body2
First maximum… efficiency
No spring energy … radiated energy
body1, body2, springs and sum of all
principle of conservation of energy for rock08
Spring energy


springs
$\beta = 1$
Maximum energy radiation now
body1
spring energy - efficiency
Maximum efficiency now

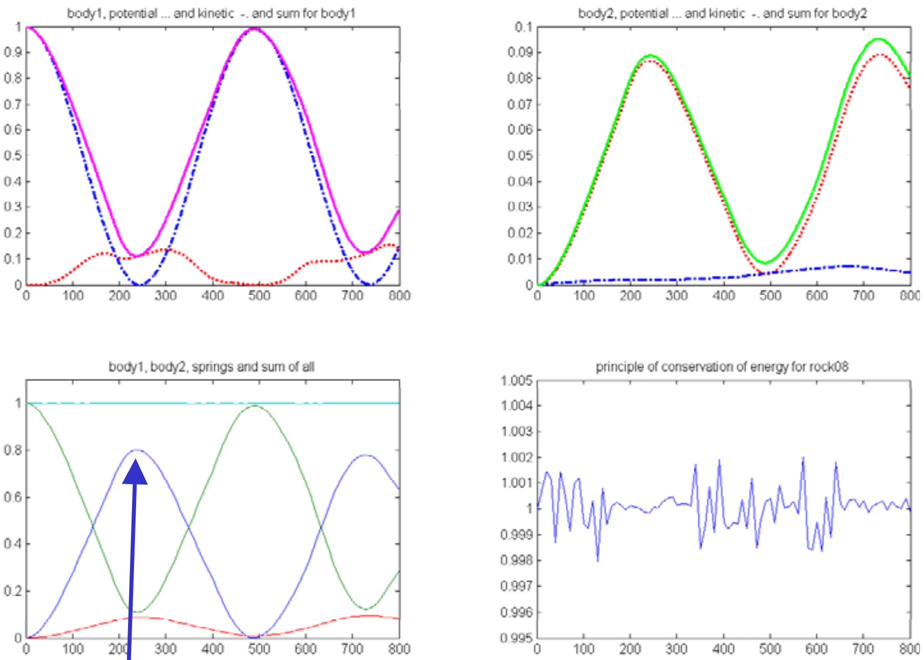
$\beta = 1$

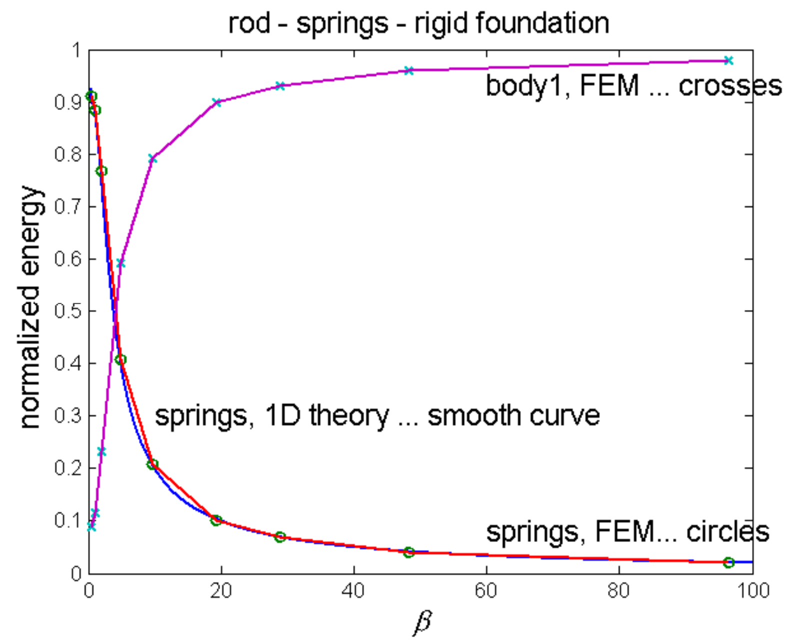


$\beta = 10$



Reminder of results with rigid foundation

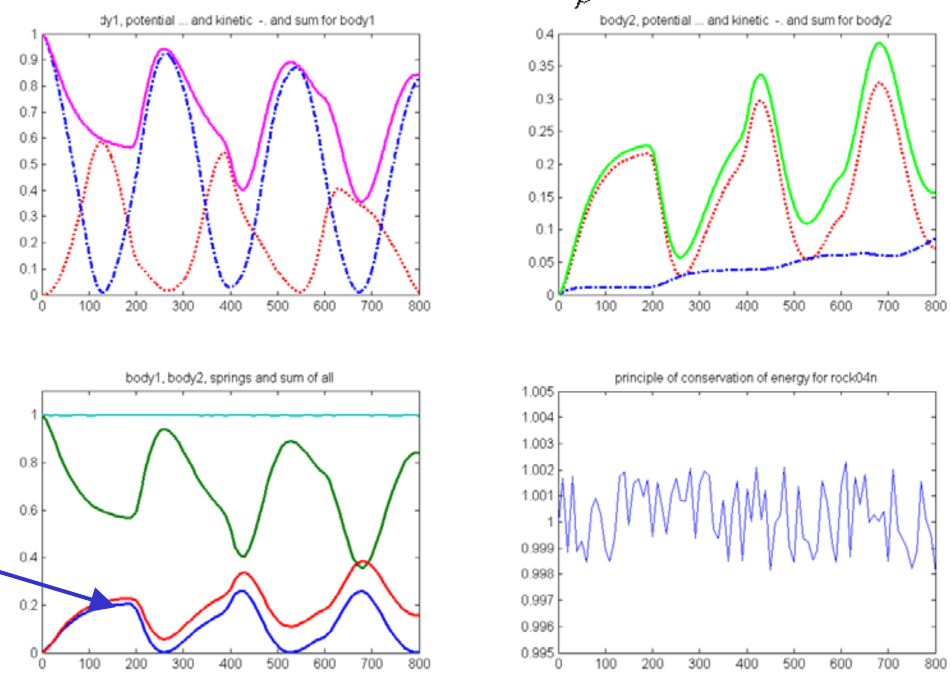


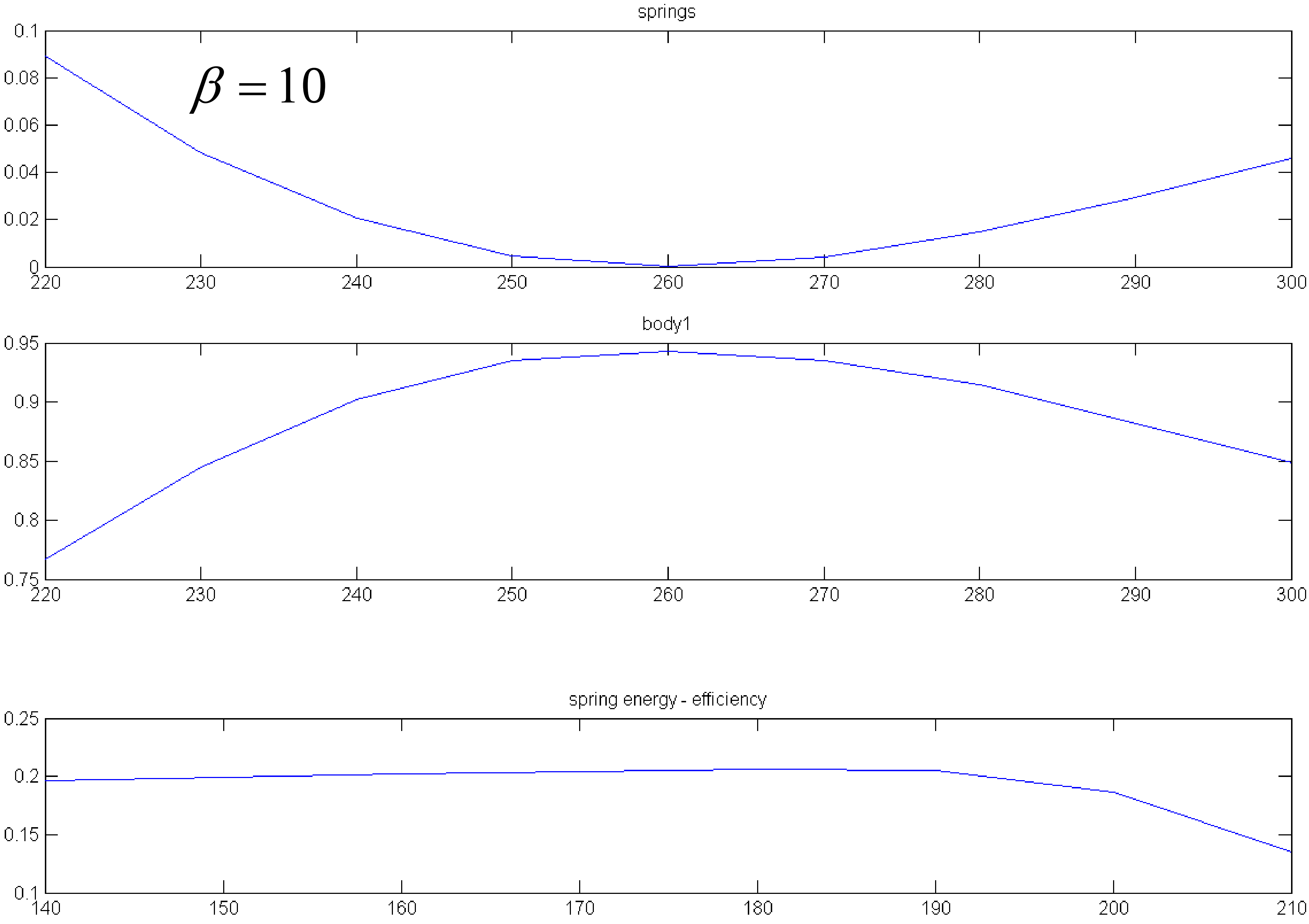


$\beta = 1$

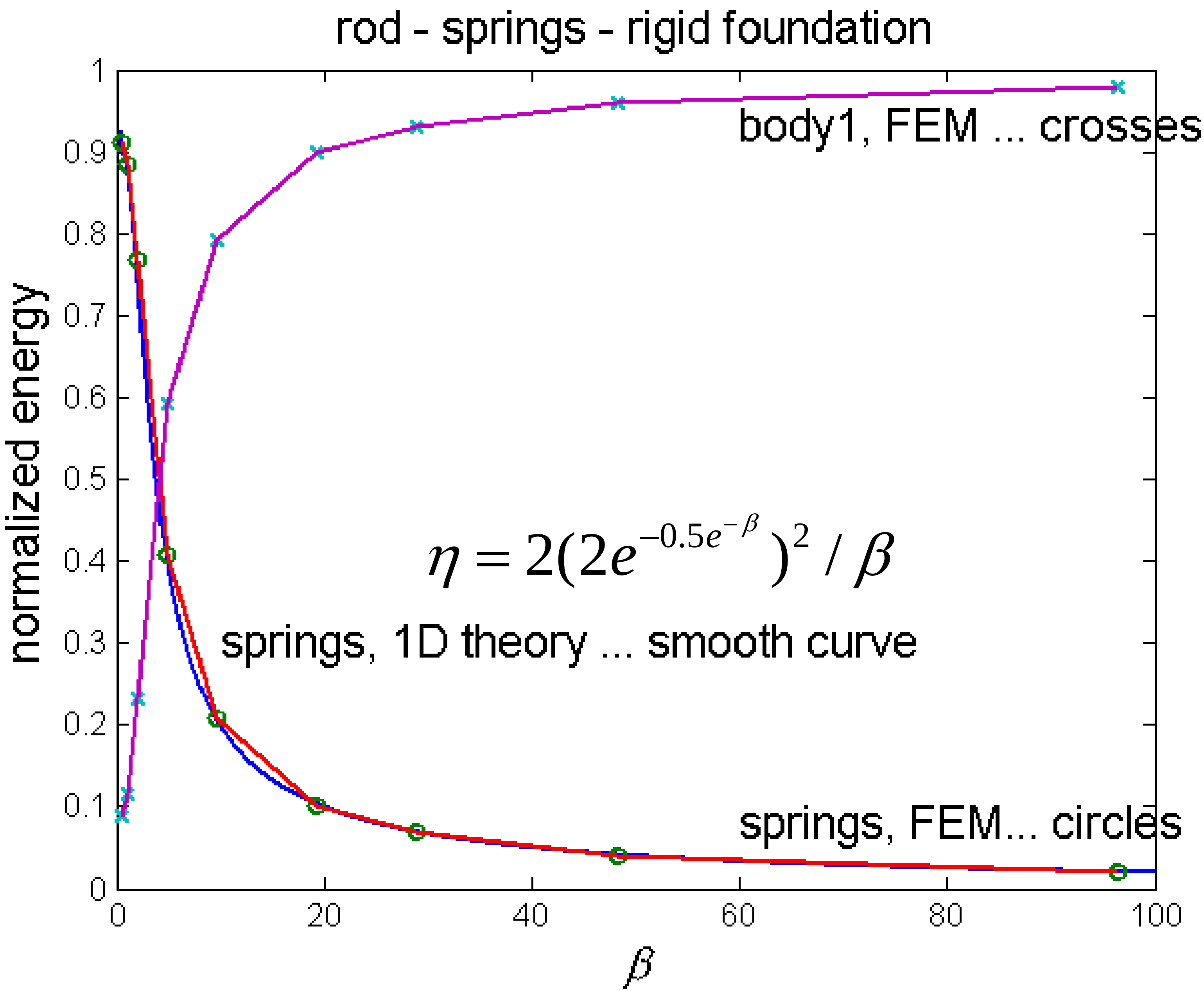
Spring energy
first maximum … efficiency

$\beta = 10$

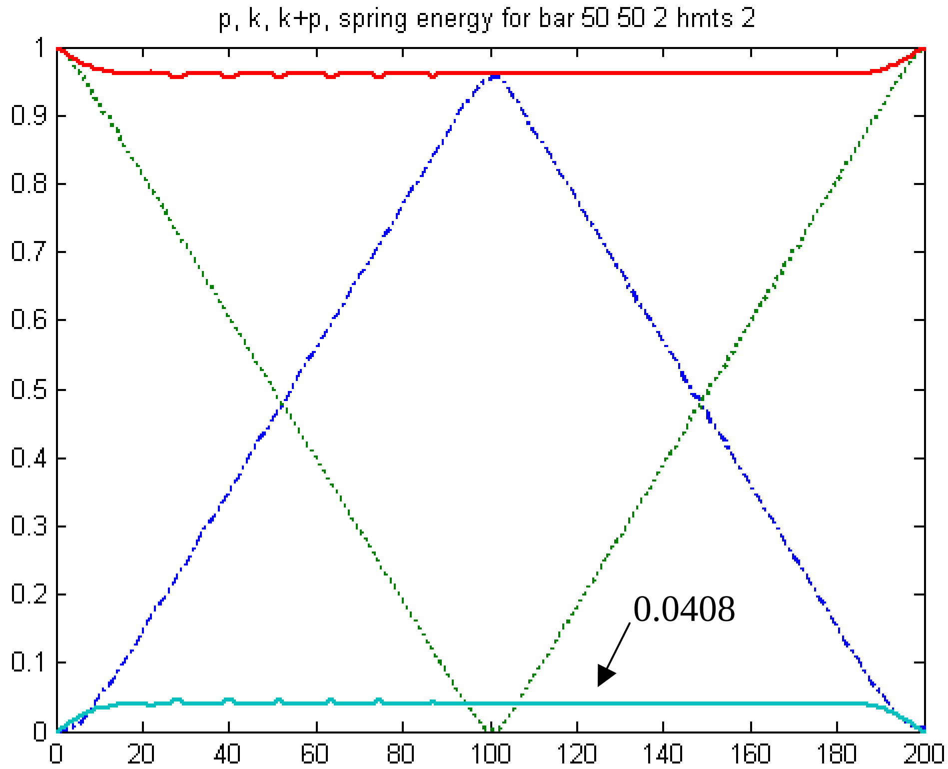



springs
$\beta = 10$
0.1
0.08
0.06
0.04
0.02
0
220
230
240
250
260
270
280
290
300
body1
0.95
0.9
0.85
0.8
0.75
220
230
240
250
260
270
280
290
300
spring energy - efficiency
0.25
0.2
0.15
0.1
140
150
160
170
180
190
200
210

Reminder of results with rigid foundation

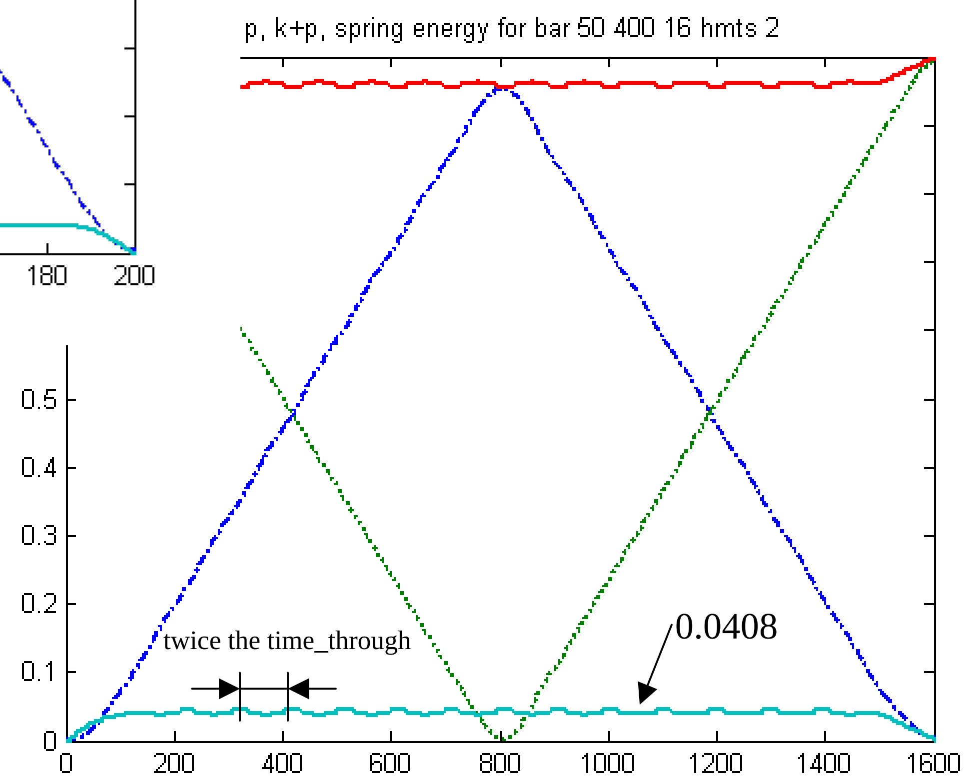


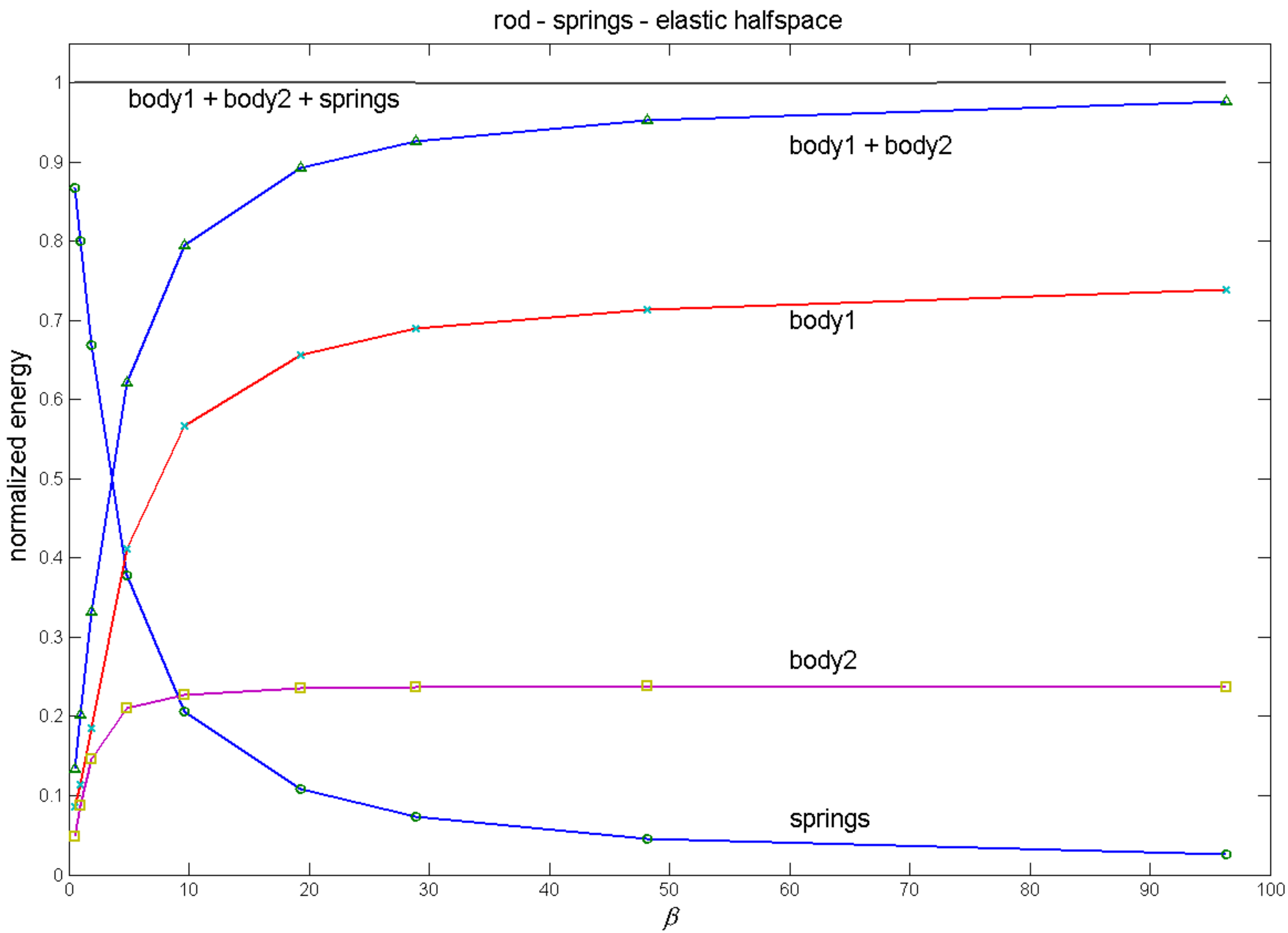
Influence of meshsize on energy computation

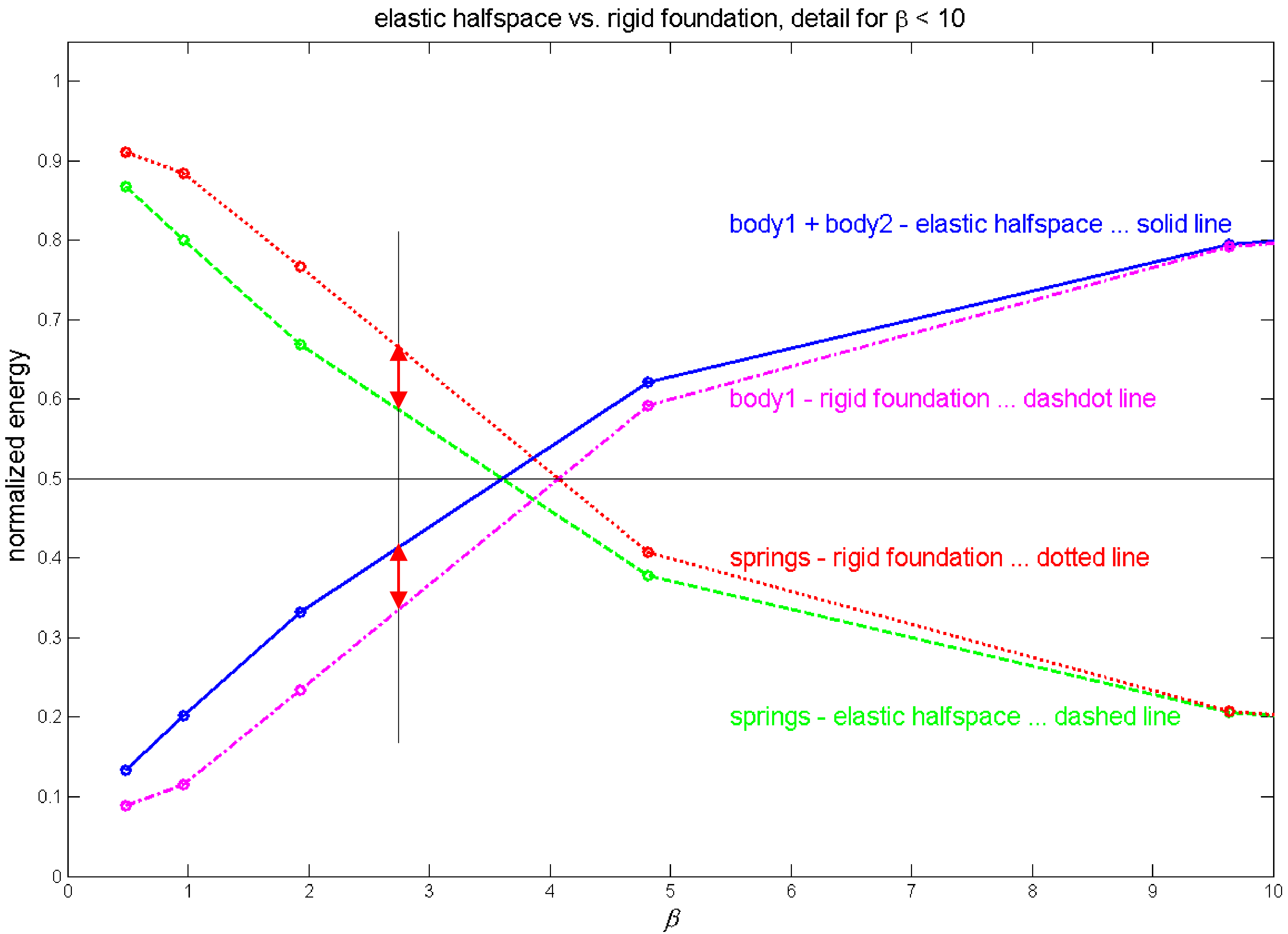


Coarse mesh

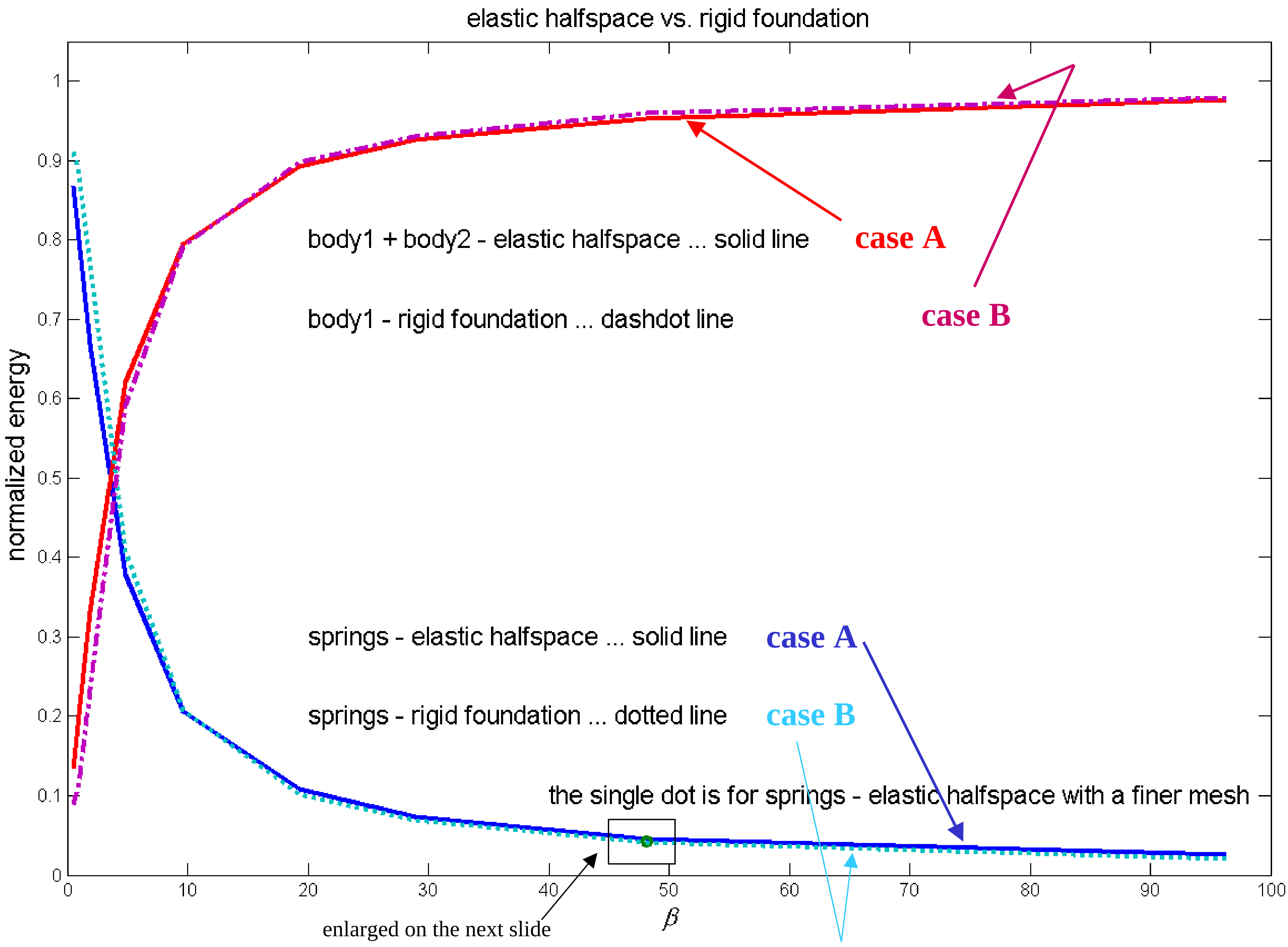
Fine mesh,
eight times smaler elements,
eight times smaller time step



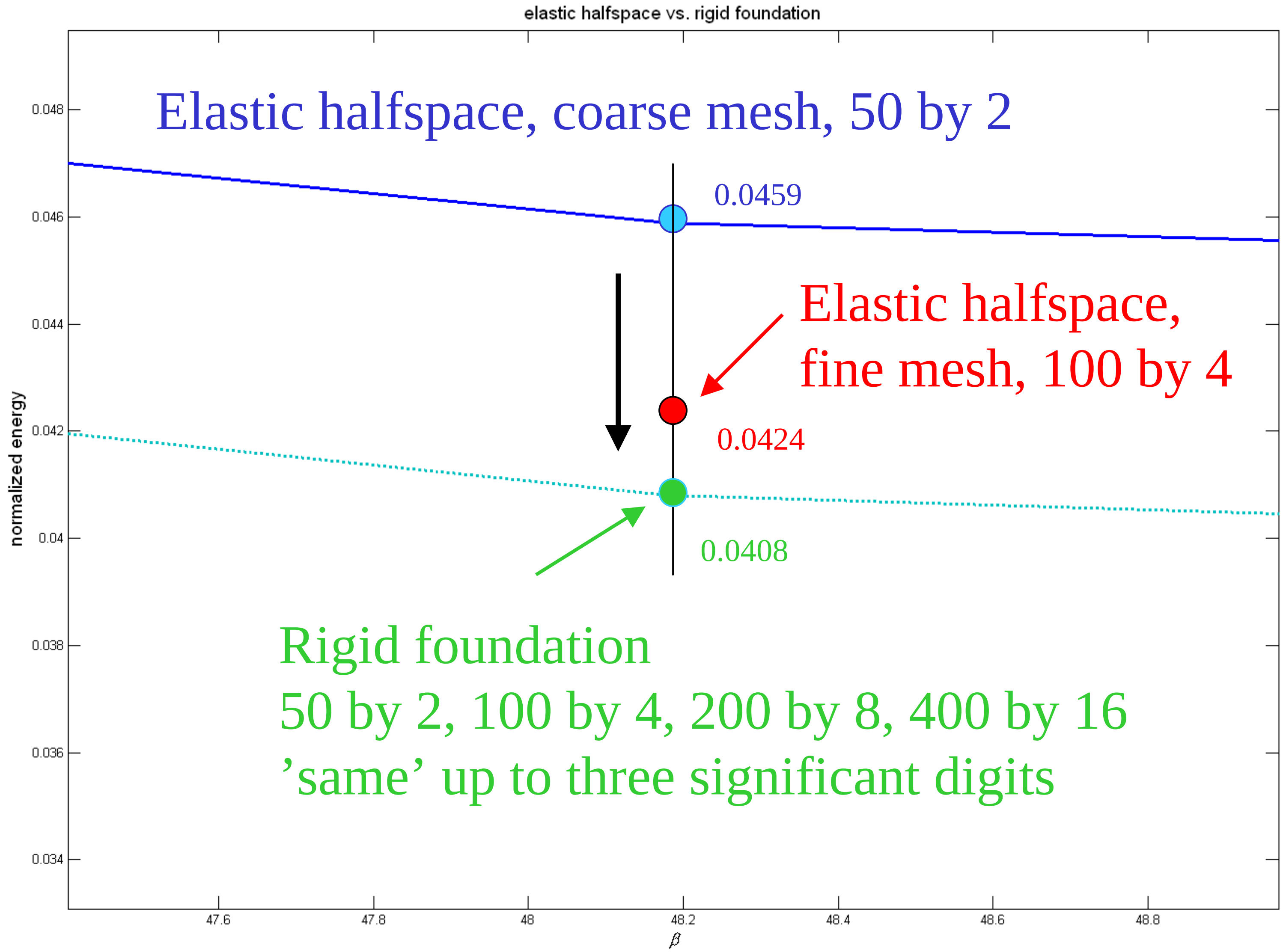

rod - springs - elastic halfspace
body1 + body2 + springs
body1 + body2
body1
body2
springs
normalized energy
β
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

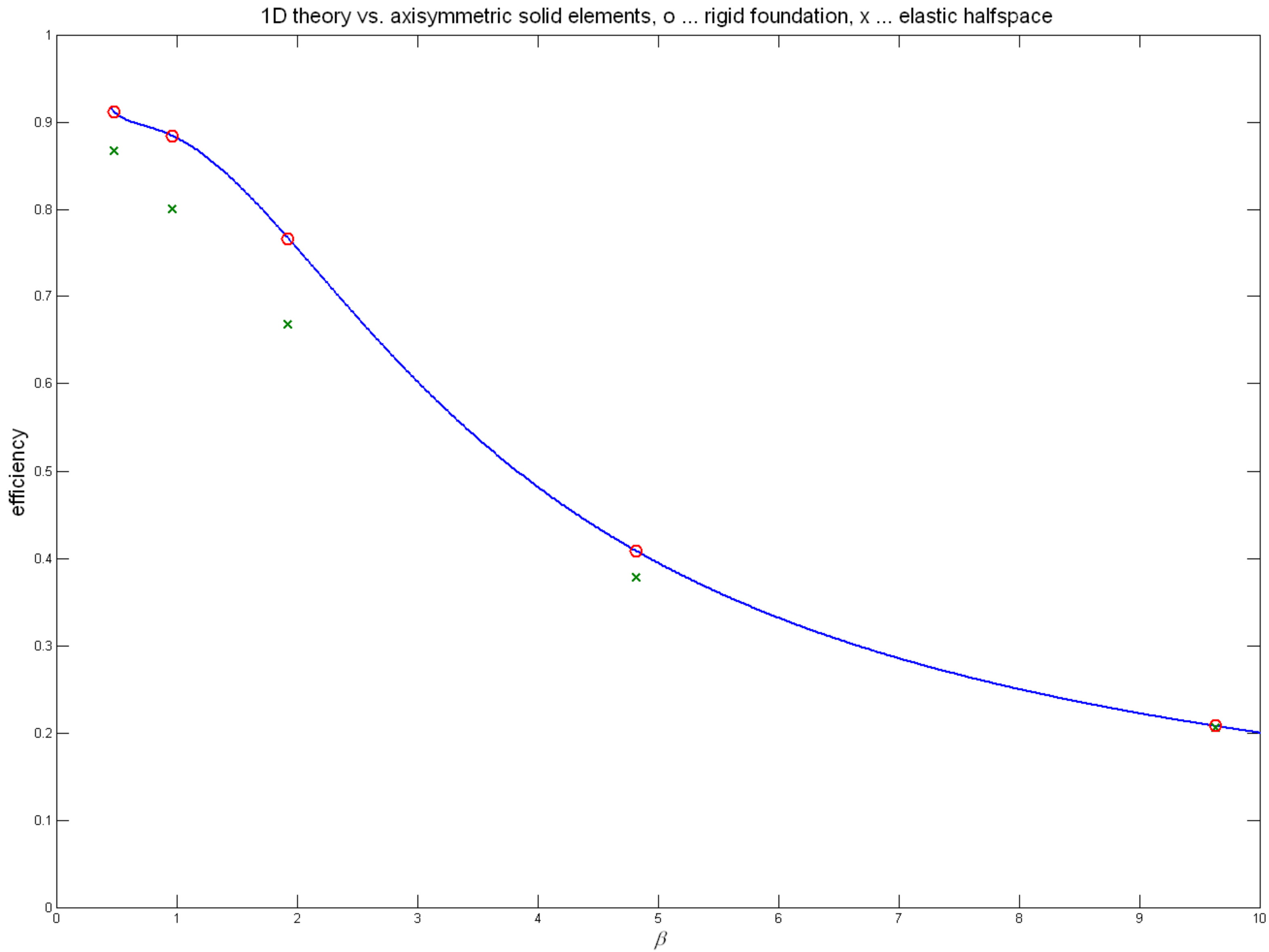


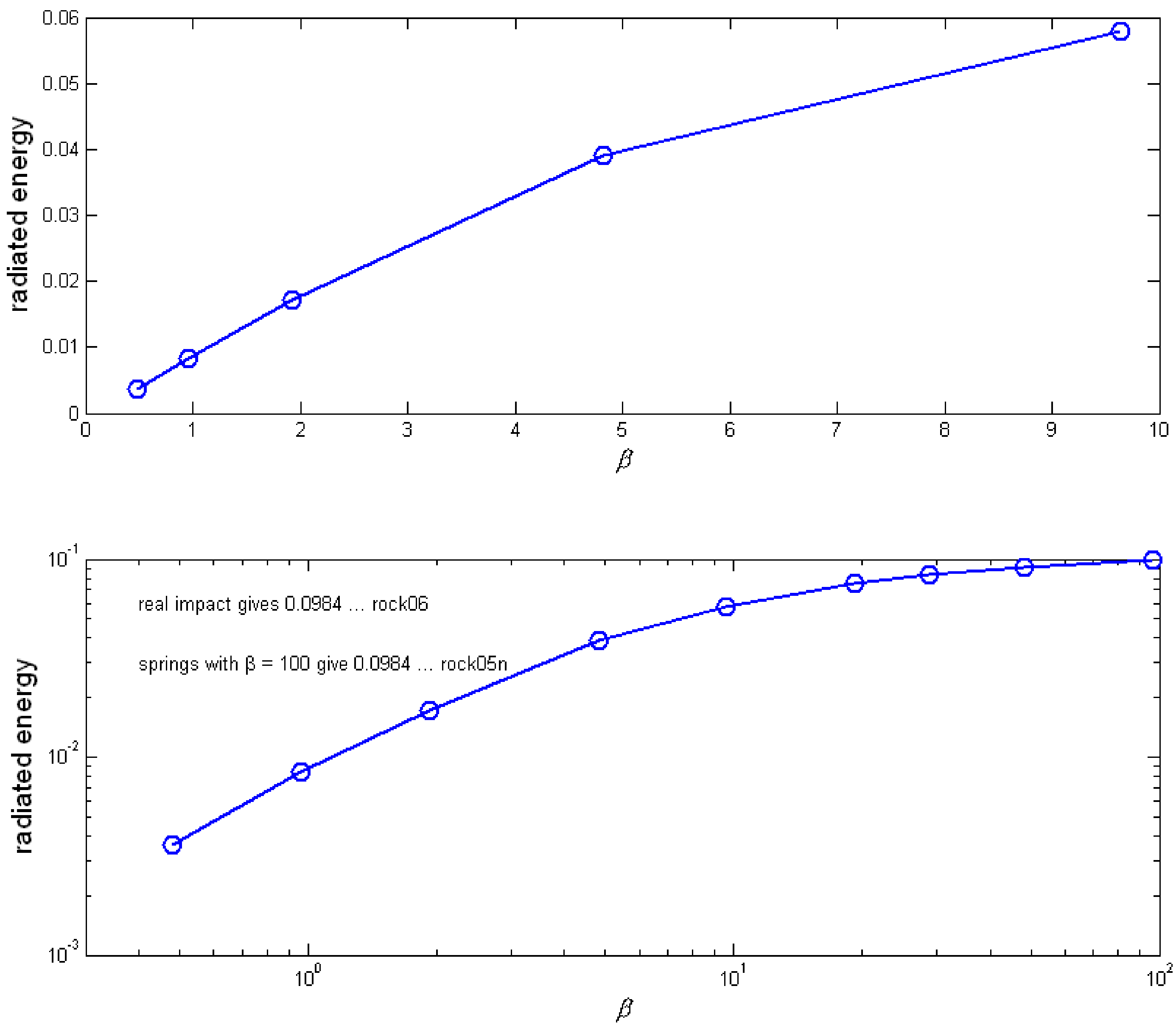
elastic halfspace vs. rigid foundation, detail for β < 10
normalized energy
β
body1 + body2 - elastic halfspace ... solid line
body1 - rigid foundation ... dashdot line
springs - rigid foundation ... dotted line
springs - elastic halfspace ... dashed line
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10



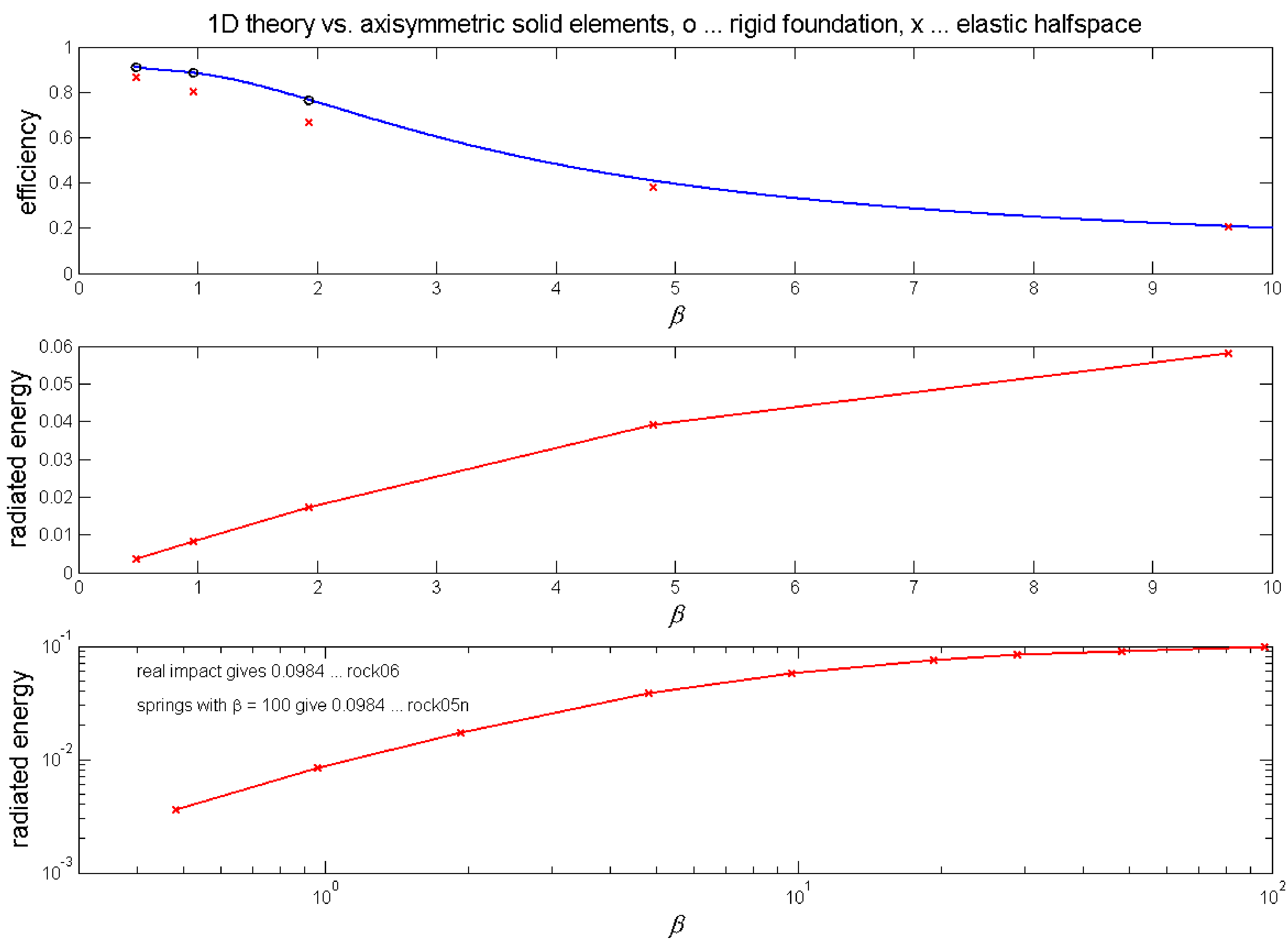
elastic halfspace vs. rigid foundation
normalized energy
body1 + body2 - elastic halfspace ... solid line
case A
body1 - rigid foundation ... dashdot line
case B
springs - elastic halfspace ... solid line
case A
springs - rigid foundation ... dotted line
case B
the single dot is for springs - elastic halfspace with a finer mesh
enlarged on the next slide
β
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100


elastic halfspace vs. rigid foundation
Elastic halfspace, coarse mesh, 50 by 2
0.0459
Elastic halfspace,
fine mesh, 100 by 4
0.0424
0.0408
Rigid foundation
50 by 2, 100 by 4, 200 by 8, 400 by 16
’same’ up to three significant digits
normalized energy
0.048
0.046
0.044
0.042
0.04
0.038
0.036
0.034
47.6
47.8
48
48.2
48.4
48.6
48.8
β


1D theory vs. axisymmetric solid elements, o ... rigid foundation, x ... elastic halfspace
efficiency
β
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10


0.06
0.05
0.04
0.03
0.02
0.01
0
radiated energy
0
1
2
3
4
5
6
7
8
9
10
β
10^-1
10^-2
10^-3
radiated energy
real impact gives 0.0984 ... rock06
springs with β = 100 give 0.0984 ... rock05n
10^0
10^1
10^2
β

Leftovers


1D theory vs. axisymmetric solid elements, o ... rigid foundation, x ... elastic halfspace
efficiency
β
radiated energy
β
radiated energy
real impact gives 0.0984 ... rock06
springs with β = 100 give 0.0984 ... rock05n
β