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Comparison of eigenvalue solvers in KRATOS MULTIPHYSICS

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May 23, 2018

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Comparison of solver settings

1. Example: Eignevalue analysis of a three-dimensional cantilever

https://github.com/KratosMultiphysics/Examples/tree/master/structural_mechanics/validation/beam_eigenvalue_anal

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 10,
            "lambda_max": 10000,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_skyline_lu_solver"
            }
        },
```

2. Wiki: FEAST solver

https://github.com/KratosMultiphysics/Kratos/wiki/How-to-use-the-FEAST-Solver-in-Kratos%3F

```
        "eigensolver_settings":{
            "solver_type": "feast",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0.0,
```

```
            "lambda_max": 2.5e3,
            "search_dimension": 6
        },
```

The simulation does not start without the definition of the linear solver.

3. Parameters and their meaning

3.1. FEAST solver

print_feast_output defines if the output of the feast solver on the terminal will be shown (true) or not (false).

perform_stochastic_estimate defines if a stochastic estimation will be done (true) or not (false).

solve_eigenvalue_problem defines if the eigenvalue problem will be solved (true) or not (false).

lambda_min defines the lower limit of the search interval for the eigenvalues.
Definition: $\lambda = \omega^2 = (2\pi f)^2 \left[\left(\frac{\mathrm{rad}}{\mathrm{s}}\right)^2\right]$.

lambda_max defines the upper limit of the search interval for the eigenvalues.
Definition: $\lambda = \omega^2 = (2\pi f)^2 \left[\left(\frac{\mathrm{rad}}{\mathrm{s}}\right)^2\right]$.

search_dimension With higher values of the search dimension, the simulations take generally longer. It the search dimension is set to a value which is too low, the results are not complete. In this case an error message is printed on the terminal.

linear_solver_settings defines which linear solver will be used. Two known possibilities are "complex_skyline_lu_solver" and "complex_pastix_solver".

3.2. EigenSolverApplication

number_of_eigenvalues defines how many eigenvalues will be calculated.

max_iteration defines after how many iterations the simulation stops, without reaching convergence of the results. If it is set to a value which is too low, the results are not complete. In this case it is printed that the convergence is not reached after the chosen maximum number of iterations.

tolerance defines the allowed tolerance of the eigenvalues. Whit a chosen tolerance of "1" or higher the results do not make sense.

echo_level If it is set to "1", after the start of the EigenSolverApplication nothing is shown on the terminal until the results are calculated and presented. If it is set to a higher value for example "2" or "1000", after the start of the EigenSolverApplication in the terminal is shown when every single iteration is completed.

Part II. Comparison of results

4. Example: Eigenvalue analysis of a three-dimensional cantilever

4.1. Model description

Kratos Multiphysics

The model used for the following studies is a cantilever beam with a width of 10 mm, a height of 5 mm and a length of 200 mm. The geometry is meshed with volumetric elements of the type hexahedron and the dimensions are $1 \times 1 \times 1$ mm. These discretization parameters results in a mesh with 10000 elements and 13266 nodes. Figure 1 shows the meshed geometry.

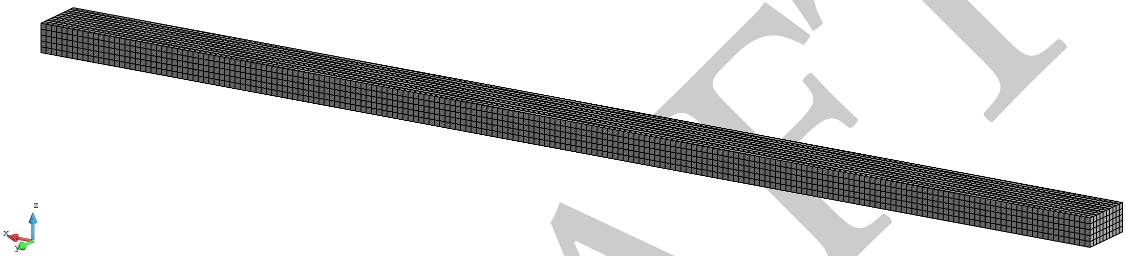

Figure 1: Meshed cantilever beam

ANSYS APDL

Aluminum, E=70000, nu=0.3. $200 \times 100 \times 5$ mm, 1 mm mesh with linear volume elements

4.2. Comparison

Many simulation runs have been performed with different parameter settings. The results are shown on table 1.

4.3. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

Table 1: Comparison with the three-dimensional cantilever

Parameters	Boundary conditions	Calculation time [hh:mm:ss]	Eigenfrequency [Hz] f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{18}
analytical	Clamped	-	103.44	206.88	648.25	1296.50	1815.11	-	3556.90	3630.23	5879.81	-	7113.80	8783.42	-	-	-	-	-	-
Feast §4.3	Clamped	00:05:33[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.4	Clamped	00:04:52[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.3	Clamped	00:07:15[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.5	Clamped	00:07:17[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.6	Clamped	00:08:13[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.7	Clamped	00:00:22[1]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Feast §4.8	Clamped	00:03:03[1]	-	-	655.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Feast §4.9	Clamped	00:05:12[1,]	-	-	-	1265.13	1817.95	2980.87	3462.72	3531.10	5719.25	5952.08	6698.18	8539.41	-	-	-	-	-	-
Feast §4.10	Clamped	00:04:39[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Feast §4.11	Clamped	00:09:09[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Eigen §4.12	Clamped	00:01:03[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Eigen §4.12	Clamped	00:01:42[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Eigen §4.13	Clamped	00:00:36[1]	104.96	207.82	655.93	1287.70	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eigen §4.14	Clamped	00:00:26[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.48	6424.72	6777.57	8652.72	-	-	-	-	-	-
Eigen §4.15	Clamped	00:00:15[1]	104.98	209.55	668.45	2303.90	3153.91	8942.36	34116.3	166805	395303	505566	798032	812900	-	-	-	-	-	-
Eigen §4.16	Clamped	00:00:33[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
Eigen §4.17	Clamped	00:01:41[1]	104.96	207.82	655.93	1287.70	1828.62	2998.13	3542.92	3561.10	5840.44	6424.72	6776.36	8642.32	-	-	-	-	-	-
ANSYS APDL	Clamped	00:00:29[2]	103.23	205.67	645.14	1274.37	1798.54	2961.73	3502.53	3506.03	5744.37	6372.00	6705.27	8500.12	8888.47	10762.95	11742.90	14825.02	15443.37	15550.31
analytical	Free	-	-	-	-	-	-	-	648.25	1296.50	1815.11	3556.90	3630.23	5879.81	-	7113.80	8783.42	11759.62	-	12267.75
FPFeast - §4.18	Free	00:06:46[1]	nan	nan	nan	nan	0.00226	0.00525	665.20	1311.21	1826.65	3557.81	3561.27	5844.57	5967.48	6822.91	8654.04	10972.9	11936.1	11963.0
ESEigen - §4.19	Free	00:34:09[1]	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	nan	8.3e-07	-	-	-	-	-	-
ANSYS APDL	Free	00:00:29[2]	0.00	0.00	0.00	0.00	0.86	0.97	654.39	1297.79	1796.97	3503.37	3521.25	5749.46	5893.00	6752.34	8513.08	10858.48	11767.93	11792.22

[1] Four processors of the type Intel Xeon CPU 5160, 3,00 GHz with 7.8 gigabyte RAM
[2] Two processors of the type Intel Core i5-3320M CPU @ 2.60GHz with 7.8 gigabyte RAM

4.4. Kratos Multiphysics FEAST - complex_skyline_lu_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_skyline_lu_solver"
            }
        },
```

4.5. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": false,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.6. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": true,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.7. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": false,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 40,
            "linear_solver_settings":{
```

```
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.8. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 1e7,
            "lambda_max": 4e7,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.9. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 10,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

==>Warning: Size Subspace M0 too small

4.10. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 20,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.11. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
```

```
            "solve_eigenvalue_problem": true,
            "lambda_min": 0,
            "lambda_max": 4e9,
            "search_dimension": 80,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.12. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 1000,
            "tolerance": 1e-6,
            "echo_level": 1
        },
```

4.13. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 5,
            "max_iteration": 1000,
            "tolerance": 1e-6,
            "echo_level": 1
        },
```

4.14. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 5,
            "tolerance": 1e-6,
            "echo_level": 1
        },
```

Convergence not reached in 10 iterations.

4.15. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 1000,
            "tolerance": 1,
            "echo_level": 1
        },
```

4.16. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 1000,
```

```
            "tolerance": 0.1,
            "echo_level": 1
        },
```

4.17. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 1000,
            "tolerance": 1e-6,
            "echo_level": 1000
        },
```

4.18. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": -10,
            "lambda_max": 2e10,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

4.19. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 13,
            "max_iteration": 1000,
            "tolerance": 1e-6,
            "echo_level": 1
        },
```

4.20. ANSYS APDL

Model built, meshed and calculated with ANSYS APDL v170 Block Lanczos solver, in which the first 18 eigenfrequencies are calculated.

5. Housing of planetary gear

5.1. Model description

Kratos Multyphysics

For the following studies the model of the housing of a planetary gear is used. In order to simplify the geometry for the simulation, in this model the internal teeth are removed. The geometry is meshed with elements of the type “tetrahedra” and with the size of 5 mm. These parameters leads to a mesh with 229558 elements and 48308 nodes. Figure 2 shows the meshed geometry. A generic steel is used with a Young’s modulus of 206.9 GPa, a density of 7.85e-9 t/mm³ and a poisson ratio of 0.29.

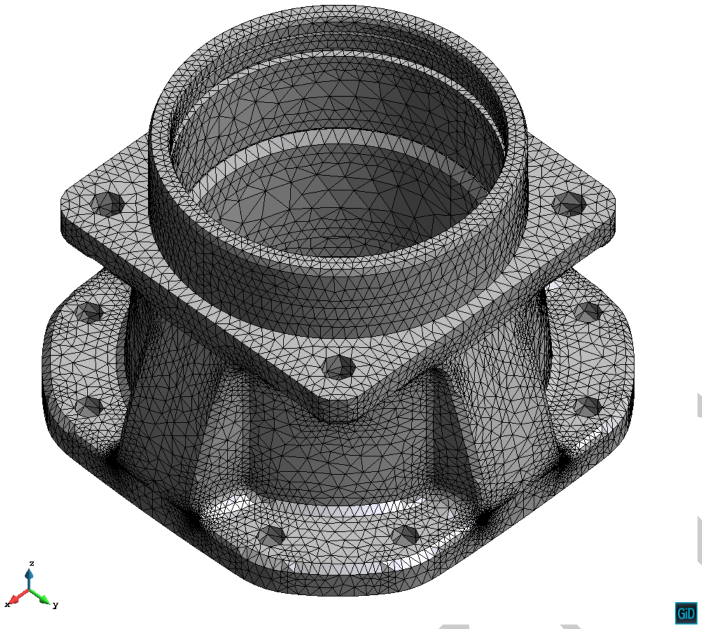

Figure 2: Meshed housing with simplified geometry

Calculix

STEP file imported into FreeCAD and meshed there with max mesh size 10 mm, which was a lengthy process. The modal analysis is then calculated with the integrated link to the open source solver Calculix. The FreeCAD–Calculix version requires a constrained model. The entire back side of the housing was then constrained. The model has 58680 nodes and 181274 elements. First five eigenfrequencies are calculated. A generic steel is used with a Young's modulus of 200 GPa and a density of 7.9e-9 t/mm^3.

5.2. Comparison

Many simulation runs have been performed with different parameter settings. The results are shown on table 2. Figure 3 shows the first five mode shapes calculated with Kratos Multiphysics.

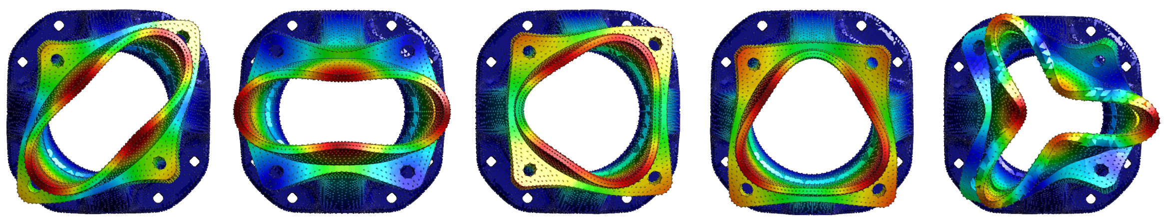

Figure 3: Mode Shapes

Table 2: Comparison with the simplified housing

Parameters	Boundary	Calculation time [hh:mm:ss]	f_1	f_2	f_3	f_4	f_5
Feast §5.3	Clamped	00:22:01[3]	8541.71	10247.4	10575.2	10578.4	13863.4
Eigen §5.4	Clamped	00:05:05[3]	8541.71	10247.4	10575.2	10578.4	13863.4
Eigen §5.5	Clamped	00:02:14[3]	8541.72	10247.4	10575.4	10578.5	13872.3
Eigen §5.6	Clamped	00:01:52[3]	8563.75	10258.5	10580.8	10683.5	14332.2
Calculix	Clamped	00:00:38[4]	8413.36	9982.08	10119.4	10128.0	14463.0

5.3. Kratos Multiphysics FEAST - complex_pastix_solver

```
        "eigensolver_settings":{
            "solver_type": "FEAST",
            "print_feast_output": true,
            "perform_stochastic_estimate": false,
            "solve_eigenvalue_problem": true,
            "lambda_min": 2.5e9,
            "lambda_max": 8e9,
            "search_dimension": 40,
            "linear_solver_settings":{
                "solver_type": "complex_pastix_solver"
            }
        },
```

5.4. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 6,
            "max_iteration": 1000,
            "tolerance": 1e-6,
            "echo_level": 1
        },
```

5.5. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 6,
            "max_iteration": 1000,
            "tolerance": 0.1,
            "echo_level": 2
        },
```

5.6. Kratos Multiphysics EigenSolverApplication

```
        "eigensolver_settings":{
            "solver_type": "eigen_eigensystem",
            "number_of_eigenvalues": 6,
            "max_iteration": 3,
```

[3] Four processors of the type Intel Xeon CPU 5160, 3,00 GHz with 7.8 gigabyte RAM
[4] Two processors of the type Intel Core i5-3320M CPU @ 2.60GHz with 7.8 gigabyte RAM

```
            "tolerance": 0.1,
            "echo_level": 2
        },
```

Part III.
Housing

Table 3: Comparison of the Housing

Parameters	Boundary	Comment	f_1	f_2	f_3	f_4	f_5	f_6
EigenSolver	Clamped		8584.81	10228.4	10500.3	10506.3	14263.0	14388.8
EigenSolver	Clamped	with mass points	1170.53	1283.11	1412.52	1423.93	1512.61	1527.74
Feast	Free		5113.80	5825.95	6105.04	6418.57	13139.3	13238.1
Feast	Free	with mass points	820.050	969.658	1456.26	1470.48	1642.07	1717.43