Contact Analysis - An Alternative Approach

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Abstract

Contact is a highly nonlinear boundary condition in Finite Element Analysis (FEA), which is used in many applications. Each assembly model has joints where contact is present. An accurate representation of the actual contact has a great influence on displacements and stresses. In fact, even very small changes in the contact geometry can change the FE results drastically.

Although contact is omnipresent in FEA applications, the standing of contact analysis is still rather poor due to high computational effort, sometimes serious convergence and accuracy problems. Such problems can also limit the possible model sizes due to increasing computing times. Users often replace true contact by other couplings and hope that the results will be acceptable. When model sizes increase due to needs for predicting durability, the situation becomes even worse.

Although contact is a nonlinear effect, the other structural behaviour is linear in many cases, i.e. no material nonlinearity and no geometrical nonlinearity is involved. But FE solvers mainly use nonlinear solution methods, where the stiffness matrix is updated iteratively to represent the contact stiffness in a suitable manner. Beside penalty methods, Lagrange methods are available, which amend the structural degrees of freedom by additional contact degrees of freedom leading to very accurate results, but the computational effort becomes hardly affordable.

In recent years, optimization methods became more popular. One important prerequisite for using optimization is that the basic analysis is running short enough to justify an optimization overnight or within one or two days. This imposes another demand on contact analysis to provide short run times. In many cases, larger contact analyses do not run fast enough to apply optimization.

When simulations with contact should earn more confidence, then alternative approaches to contact analysis have to be investigated. It is the purpose of this paper to explain an alternative FE contact analysis method and to present a number of examples to show the broad application field and its benefits.

1. Introduction

There can be no doubt about the importance of contact for accurate results in Finite Element Analysis (FEA). Due to its highly nonlinear character, contact can drastically increase run time, which makes contact an undesirable obstacle for delivering analysis results in time. Moreover, verification and validation of contact models and results are difficult and cumbersome. Even though one cannot expect to facilitate every aspect of contact analysis, this paper wants to talk about accuracy and speed.

The current solution strategies in contact can be classified as penalty methods on the one side and Lagrange methods on the other. While penalty methods have the image to be fast, their accuracy seems to be at least dubious. In contrast, Lagrange methods are seen as giving accurate results, but their speed seems to be considerably lower than penalty methods. This observation describes the motivation to think about the possibility of a new approach to reconcile accuracy and speed.

There are a few trends in the application of structural simulation, which enforces this motivation:

- Model sizes are always increasing in order to improve the quality of stress results. This is a crucial point, because stresses in FEA always have a diminished precision of one order compared to displacements.
- Because stresses are often used to predict safety factors or fatigue life, model sizes are pushed additionally. This is mainly due to the stress gradients, which show an extra diminishing of one order in precision.
- Though model sizes are increasing, automatic optimization of structures are evolving and lightweight designs are becoming more important. There, contact phenomena cannot be excluded from these requirements.

All of these trends push the need for higher speed in contact analysis without sacrificing accuracy.

2. Lagrange Contact Conditions

Fig. 1 shows the main idea of contact, where without contact two bodies under external load may penetrate each other. This is not allowed in contact analysis. In addition, contact is always under compression and tensile forces in contact are not possible. But compression occurs only, when the bodies are in contact. These conditions are referred to as Hertz-Signorini-Moreau conditions [1].

To fulfil these conditions, one has to determine the contact force R_C. Then, external and contact forces define the loading to get the right displacements of the structure under contact.

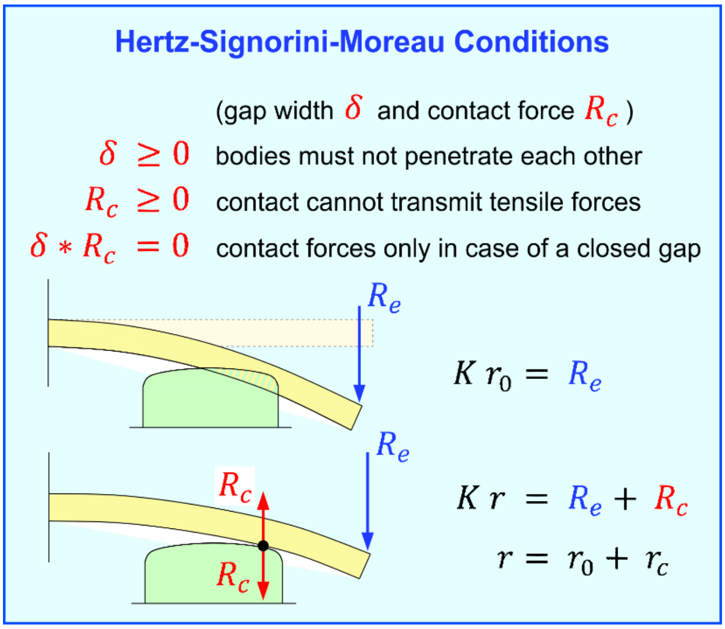


Figure 1: Hertz-Signorini-Moreau conditions of frictionless contact

Although the Hertz-Signorini-Moreau conditions are set for frictionless contact, they are still valid for frictional contact but additional conditions have to be taken into account, e.g. Coulombs law of friction. More information on how to implement these conditions are discussed in [2].

3. Flexibility

From Fig. 1, one can derive the basic idea to solve contact analysis tasks. When forces are the unknowns while displacements are already known, a flexibility equation is the appropriate representation of the problem (see Fig. 2). In contact analysis, the displacements are indeed already known, e.g. the initial status of the contact gaps.

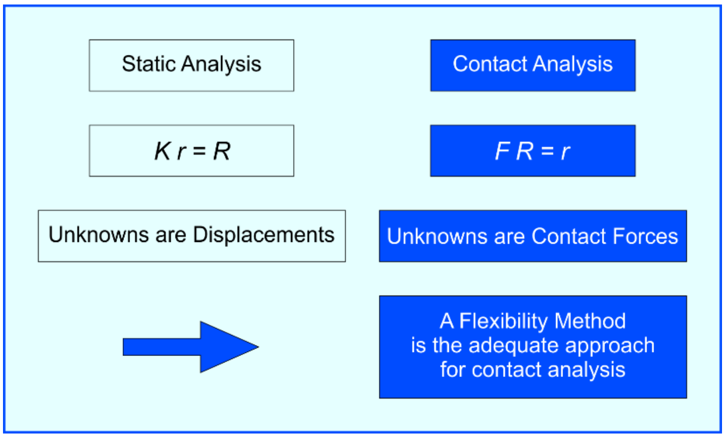


Figure 2: Contact solving strategy using flexibility method

With the flexibility at hand, it is easy and straight forward to calculate the contact forces. Of course, the overall conditions are nonlinear and therefore one has to use nonlinear solving techniques.

4. Condensation

The classical approach to solve contact tasks is based on the stiffness matrix. Therefore, this method is sometimes named stiffness method in order to denote the difference to the flexibility method. The stiffness method using the Lagrange Contact Conditions is extending the size of the stiffness matrix by the number of active contact degrees of freedom (see Fig. 3), while the flexibility method can be used to condense the matrix size to those contact degrees of freedom only, thus avoiding the repeated assembly and decomposition of the global stiffness matrix during the contact iteration.

Using a penalty method on the stiffness side will not enlarge the stiffness but will add stiffness values to the matrix to fulfil the Hertz-Signorini-Moreau conditions. Nevertheless, also for this method the global stiffness matrix has to be recalculated repeatedly.

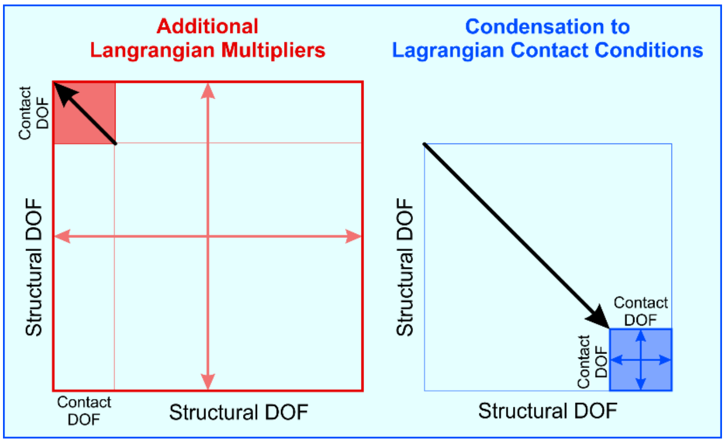


Figure 3: Condensation of flexibility matrix

5. Condensed Lagrange Flexibility (CLF) Solver

Combining condensation, Lagrange contact conditions, and flexibility method will result in the CLF method and solver. These main ingredients represent the new approach in contact analysis which aims to deliver high accuracy together with very short computation times.

Some important consequences from this approach are discussed in the subsequent sections.

6. Embedding

It is important to mention here, how a static analysis communicates with the contact solver to generate a joint result. This is realized by embedding the contact solver in a (linear or nonlinear) static solver (see Fig. 4).

The particular importance of embedding contact in a linear static solver lies in the ability of this combination to solve for nonlinear contact in a linear environment without taking classical nonlinear solvers into account. This has a significant effect on computation time.

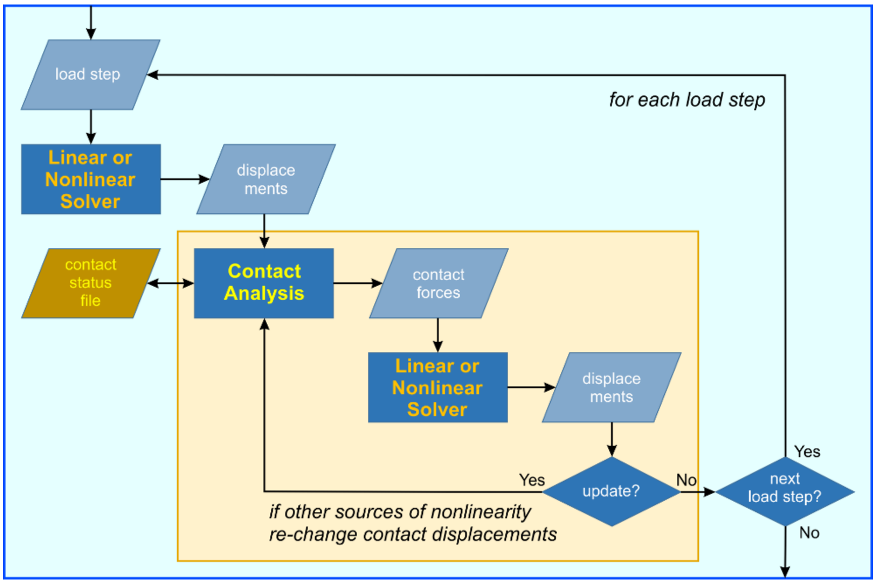


Figure 4: Embedding of contact analysis in linear or nonlinear solvers

Fig. 4 shows two loops, one over all load steps of a static analysis, and one over a possible contact update, where the displacements of a first contact analysis will influence the contact considerably, which requires an iteration to find the effective contact position and results.

The combination of a linear static solver with the contact solver allows for all nonlinearities, which are handled by contact analysis, like contact update, press fits, pretension effects, and gasket loading and unloading.

7. Accuracy

To prove accuracy, theoretical results are the best choice. There, the solutions of Hertz contact provide a number of cases to check the accuracy of a contact result. In Fig. 5, the contact between two spheres of different diameter is used to compare the theoretical result with the FE result. The results show a very good agreement between theory and simulation.

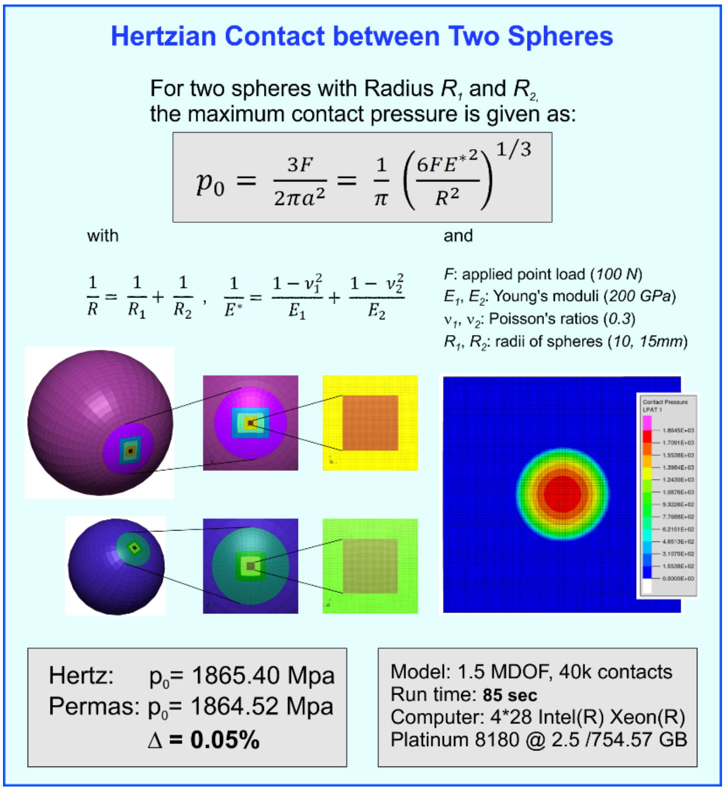


Figure 5: Accurate Hertzian contact between two spheres

8. Speed

After solving a contact analysis case, the final iteration is stored on a small contact status file (CAS file), which can be used as starting status, when a variant of the model is computed again. This is a restart capability of contact analysis (see Fig. 6). Dependent on the modification of the model, the contact status can be very close to the new solution, which is then saving computation time. For example, this feature is used in optimization tasks with contact leading to an additional significant reduction of overall run time.

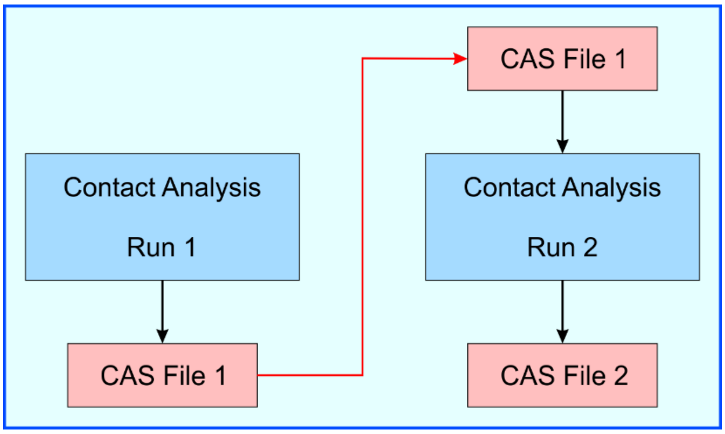


Figure 6: Application of contact status files

Fig. 7 shows an example on the effect of using CAS files. The run time with CAS file is about a factor of 10 faster than without CAS file. So, when repeating the analysis with CAS files, the run time is drastically reduced.

Engine with Assembly and 360° Crank Shaft Revolution

Nodes	2,605,313
Elements	1,603,484
Unknowns	7,363,408

CA DOF	44,387
- normal	29,815
- frictional	14,572

Linear static analysis for 70 load steps:

1. analysis (no CAS files): **07h23m**

2. analysis (with CAS files): **47m** → **Factor 9.8**

*112 cores (4*Intel-Platinum-8180) @ 2.5 GHz, 768 GiB*

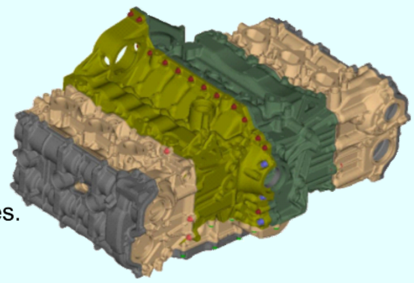
Figure 7: The effect of contact status files

In the following, a number of examples is presented to show the applicability of the CLF contact analysis and the related impact on computation time.

Fig. 8 shows an example of an IC engine, where a linear solver has been used with contact analysis. The model size is the largest in this paper and it shows that model sizes increase, when run times become shorter. So, the run time of about 5h will for sure open the door to much larger models.

Model:
19 Million nodes,
13 Million elements,
56 Million DOF,
contact, gasket,
bolt pretension,
two temperature states.

Analysis:
Static analysis,
37 time steps with different loads,
with contact status files.



Run Time:
4:48 h,
CPU/Elapsed = 62.5
(corresponds to 300 h
without parallelization)

Hardware:
4*Intel Xeon Platinum 8180
(4*28 = 112 cores (2.5 Ghz),
768 GB memory,
5.4 TB scratch
(4*Intel DC P3600 1.6 TB).

Figure 8: IC engine contact analysis

Contact in a wire harness between a car body and its doors is shown in Fig. 9. The stress analysis of this wire harness mainly depends on contact:

- Contact between the conductors of the wire.
- Contact between the convolutions of the bellow at the outer side and at the inner side of the bellow.
- Contact between wire and the inner surface of the bellow.

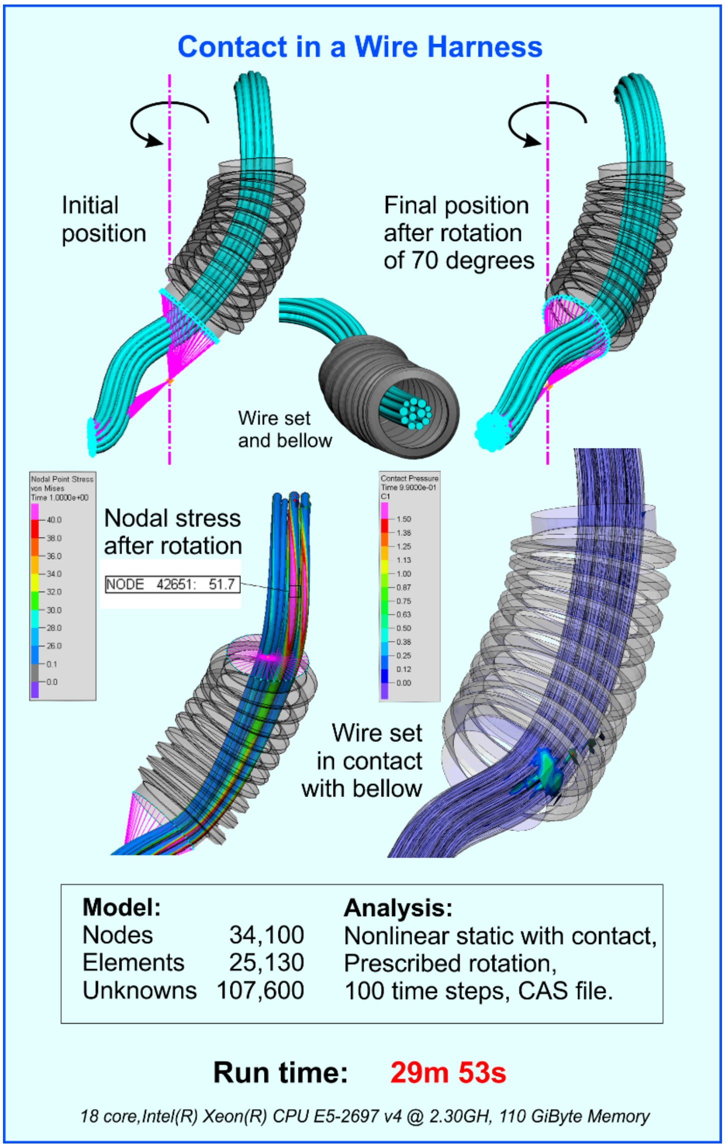


Figure 9: Wire harness with contact between all parts and self-contact of the bellow

In case of rotating structures, nonlinear FEA is used to get the stress distribution in a wide range of rotational angles. Fig. 10 shows a model of a CVJ (Constant Velocity Joint), where inclination of one angle and a complete rotation have been analysed in one computation run. Contact is taken into account between all members of the model:

- Contact between outer race and balls,

- Contact between inner race and balls,
- Contact between retainer and inner race, outer race, and balls.

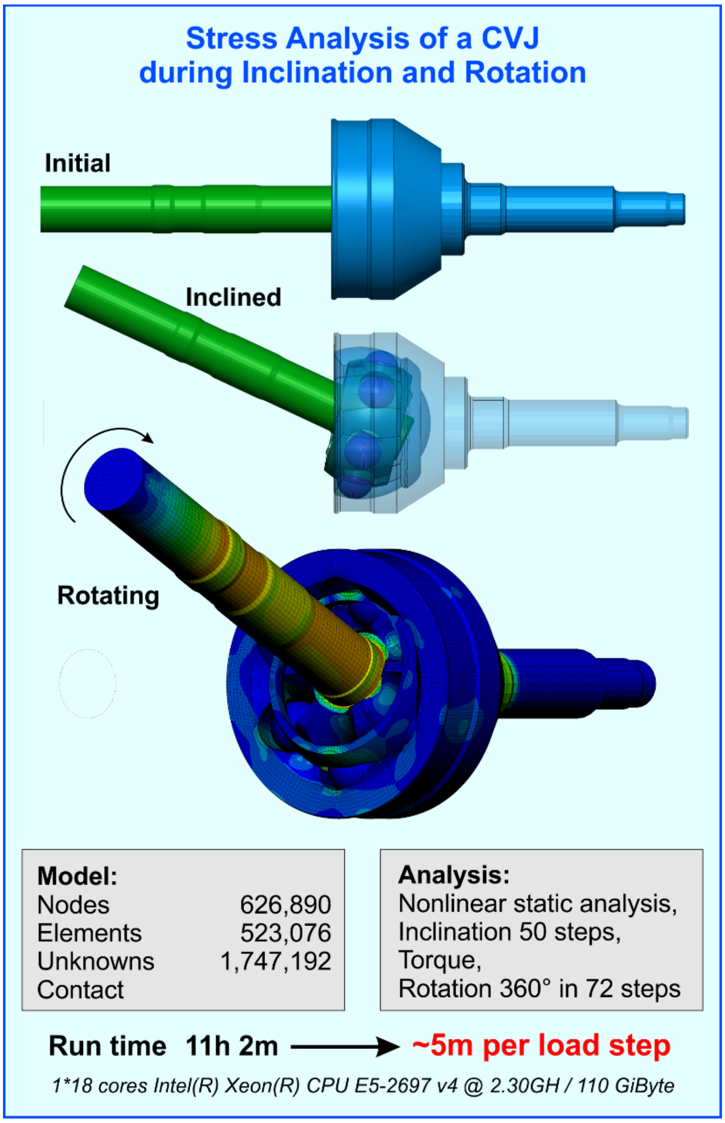


Figure 10: Large rotations with contact for a CVJ

9. Optimization

After showing the speed of the CLF contact solver, the effect on structural optimization with contact will be shown, too. Fig. 11 shows the freeform optimization of a cylinder head embedded in a complete engine analysis with a full range of loading cases. The target is to reduce high stresses at the surface of the water jacket in the cylinder head in order to reduce the risk of fracture. To this end, the coordinates of the surface of the water jacket are modified in normal direction and the inner nodes of the cylinder head are relocated to keep the element quality at a high level. In [3] another industrial example of shape optimization with contact is documented.

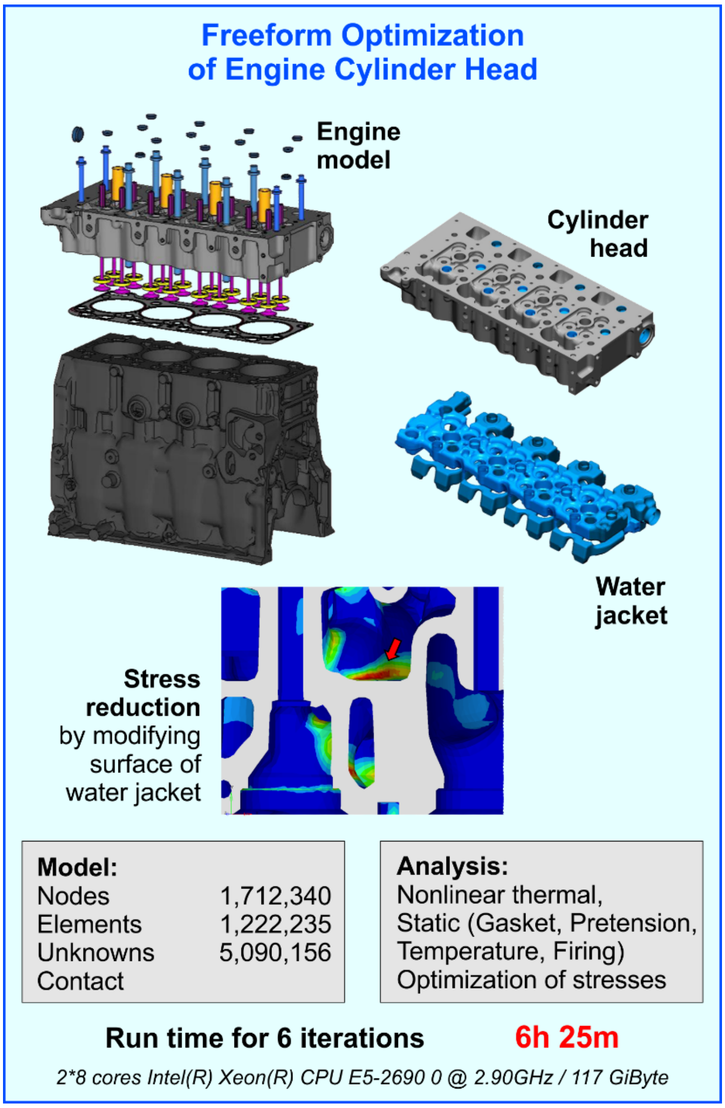


Figure 11: Stress optimization of a cylinder head

10. Conclusion

In the previous sections, it has been shown that an alternative approach in contact analysis opens a chance to fulfil accuracy requirements and to increase the speed of contact analysis simultaneously (see Fig. 12). The concept of the Condensed Lagrange Flexibility (CLF) contact solver has been proven to allow contact analysis even for really large and complex models.

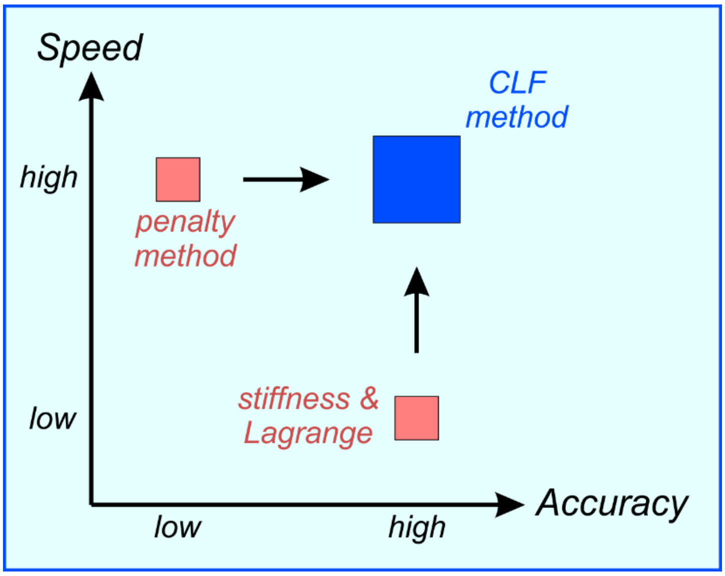


Figure 12: Improvement of accuracy and speed by new contact analysis approach

11. References

[1] Wriggers, P. (2006). *Computational Contact Mechanics*. Springer. P. 71.

[2] Rösle, H., Ast, M., Schenk, R. (1998). *Finite Element Analysis of Shrink-Fit Shaft-Hub Connections*. Proceedings of VDI Conference on Shaft-Hub Connections.

[3] Helfrich, R., Schünemann, A., Weber, S., Kienzle, A. (2017). *Weight Optimization of a Transmission Housing*. Proceedings of SIA Congrès Simulation.

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