PERFORMANCE BREAKTHROUGH IN ENGINE ANALYSIS

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THEME

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SUMMARY

Development of lightweight, low fuel consuming engines is one important component to achieve sustainable mobility. Virtual engine development is established since several years. Finite Element (FE) analysis is an accepted method in this area to analyze and improve the structural behaviour of engines. But the current long-lasting calculations prohibit a big number of variants and the usage of optimization methods.

A new much faster method for the solution process of gasket element based on the flexibility matrix [1], the inverse of the stiffness matrix, is introduced. Subsequently, the method will be presented at several engine analysis examples. All examples are state of the art engine models from the automotive industry. The drastic reduction in calculation time on the same hardware with the new method compared to the classic method will be analyzed in detail.

The performance breakthrough in virtual engine analysis by drastic reduction of analysis time allows extensive variant analysis. This opens a door to mathematical optimization methods for the simulation of engines with realistic nonlinearities in a reasonable time frame. This results in development of more efficient engines by much better understanding of the structural behaviour.

1: Introduction

In the virtual development of engines based on FE analysis a breakthrough of analysis speed is strongly needed. In the past few years parallelization and faster hardware has helped to hide the moderate improvements on the method side. But with slower acceleration of the CPU speed only improvements of the methods will show considerably shorter run times.

During the same time the model become finer and from this follows that the number of unknowns increases. The two boosters behind the model size increase are higher accuracy of finer meshes [1] and less human resources that are needed for automatic meshing. In the past a lot of human working time was used to create special geometry adaption for FE analysis and for meshing with special emphasis to reduce the number of degrees of freedom (DOF) for engine models (see Fig. 1).

Today the original CAD geometry and automatic meshing is used for engine models resulting in drastically reduced human working time to create a mesh. But on the other hand the element size is reduced to get a reliable process also for detailed geometries. Therefore, the number of DOF and the calculation time is increased.

The reduction of the fuel consumption is very important today. This target should be accessed by a virtual development process that investigates more variants to get the best product. The methods to create more models in shorter time are ready to use, so it is only the next logical step to improve the methods of analysis to go in lockstep with the needs. Emphasis should be put on the efficiency of FE analysis by process improvements inside the solver and the associated new methods in the solution process.

Static engine analysis is characterized by three important non-linear effects. First is the contact analysis, second non-linear material like plastic behaviour, tension and different compression behaviour of cast iron material, gasket material from measurement of the gasket layer and as third part the description of the non-linear load history. The non-linear load history should include assembly with bolt loading, temperature load for different temperature distribution states and working load with gas pressure in the cylinder.

In the following sections a new solution method for the gasket elements with drastic reduction of overall run-times will be introduced. Three examples for different use cases will demonstrate the advantages of the solution for the development in the engine industry.

2: Contact Analysis with Flexibility Method

In the past a big variety of solution schemes for the numerical treatment of contact boundary conditions have been developed, e.g. Lagrangian parameters, penalty functions or staggered u/p iterations [1, 2, 3, 4]. In the following, we will use a slightly modified flexibility method which exactly simulates the discontinuity of the contact region. This method shows an excellent efficiency [5].

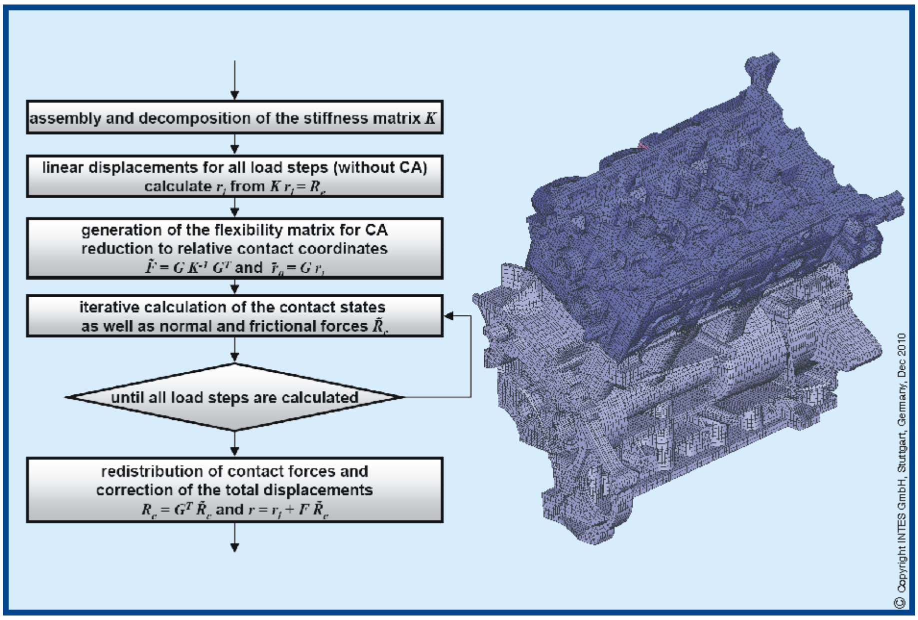

Figure 1: Flexibility method for contact analysis and half of a V6 engine (by courtesy of Ford Motor Company)

Fig. 1 shows the complete algorithm for a linear static analysis of several load steps with contact. Starting with the global stiffness matrix K and the applied forces R_e a linear-elastic solution r_l is calculated first without consideration of the contact boundary conditions. This solution is then transformed to a significantly smaller system which contains only the relative displacements of the potential areas of contact. A condensed flexibility matrix $\tilde{F}$ is then built for the contact system. During subsequent iterations the contact is closed or opened at all potential locations, respectively, until penetration is compensated by reaction forces and a state of equilibrium is reached. Finally the contact forces are transformed back into the original displacement coordinate system and the global displacements are corrected by the relative displacements of the contact zones.

The efficiency of the solution scheme is primarily based on the reduction of the non-linear system of equations. Even models with several million degrees of freedom usually have only a few thousand contact pairs. So the size of the flexibility matrix is much smaller than the stiffness matrix. A modern iteration algorithm [6] with a convergence by far superior to the common load step methods [5] contributes to the excellent performance. In addition, the convergence improves with the complexity of the model. An additional advantage of the flexibility method is its numerical accuracy. Because of the strong influence of micro-slipping on the frictional forces and corresponding effects on the resultant calculations, it is essential to minimize numerical errors. Algorithms using penalty functions do in general lead to worse condition number of the stiffness matrix. The resulting numerical error in the displacements may be of the same amount as the relative movement of the contact pairs.

In contact analysis it is important to fulfil the boundary conditions as exactly as possible [7, 8]. If the discontinuity is exactly fulfilled, the normal contact has no respective infinite stiffness. Also frictional contact is ideally simulated, even anisotropic friction is supported.

3: Nonlinear Material Analysis

The task of the solution process for non-linear materials is the handling of any material description. Typically, non-linear material of cylinder head, crankcase or bolts is used in engine analysis. Besides classical elastic-plastic material properties, sometimes a cast iron material law is required where the non-linear material behaviour in tension and compression domain is significantly different (see Fig. 2).

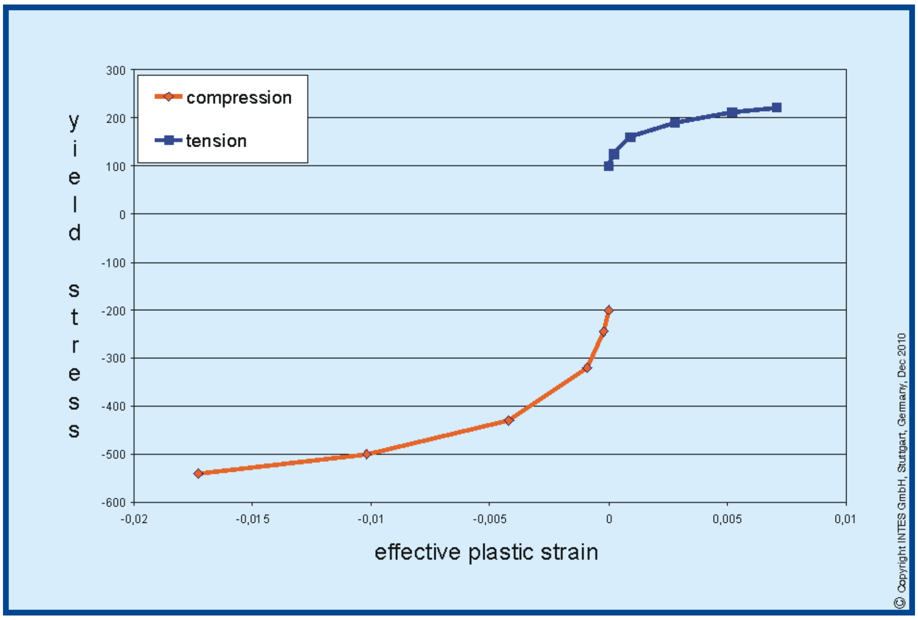

Figure 2: Cast iron material data

Both material laws are handled by input of a strain-stress relation. Also the characteristics are very similar, so the algorithms for the solution process can be specialized to them for the most efficient overall solution process. If plastic or cast iron material non-linearity is taken into account for engine analysis, a big fraction of the number of overall elements will be affected.

For engine analysis the third material, gasket material, is of utmost importance, because it has a big influence on the overall behaviour. Non-linear gasket material has a totally different characteristic. Description is made by the behaviour orthogonal to the sheet plane through all sheets by a measured pressure/closure curve (Fig. 3).

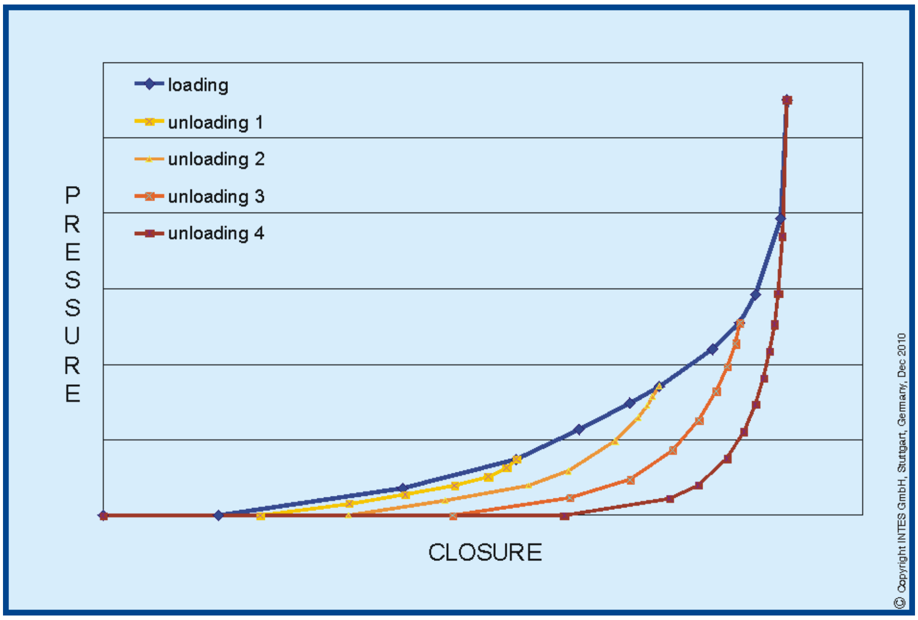

Figure 3: Pressure/closure material behaviour of gasket from measurement

The material is elastic or plastic, has one loading curve and several unloading curves, which describe different unloading paths dependent on the load state. For different areas of the engine gasket, like bead, half bead or body, individual measurements are done. So, different properties are used at several regions of the gasket layer. Very typical is the ascending slope of the curve in opposite to the classic weakening material laws. The in-plane material characteristic is linear elastic. The number of gasket elements is very small in comparison to the number of all other elastic elements.

The different behaviour of material non-linear elements and gasket elements and their different function is quite essential. But up to now both are solved by one common iterative process (see Fig. 5A). If the contact analysis with flexibility method, as described in the first section, is used, the non-linear material solution embraces with an iterative loop the contact iteration loop.

This loop is very time consuming, because all operations are done with the whole stiffness matrix.

4: Process Modelling – Non-Linear Load History

For the analysis control the specification of the load history is very important. Fig. 4 shows a typical example for a load step control where the load steps are arranged from the bottom to the top and the abscissa represents the virtual time steps of the process during non-linear analysis. Pretension and locking of several bolts and loading/unloading of gas pressure take part in this example during the four load steps.

For an engine with a higher number of cylinders there should be also a higher number of load steps, because the gas pressure has to act on all cylinders separately in a specific sequence. Also the changes of temperature states and the associated changes in stiffness can be investigated and results in a higher number of steps.

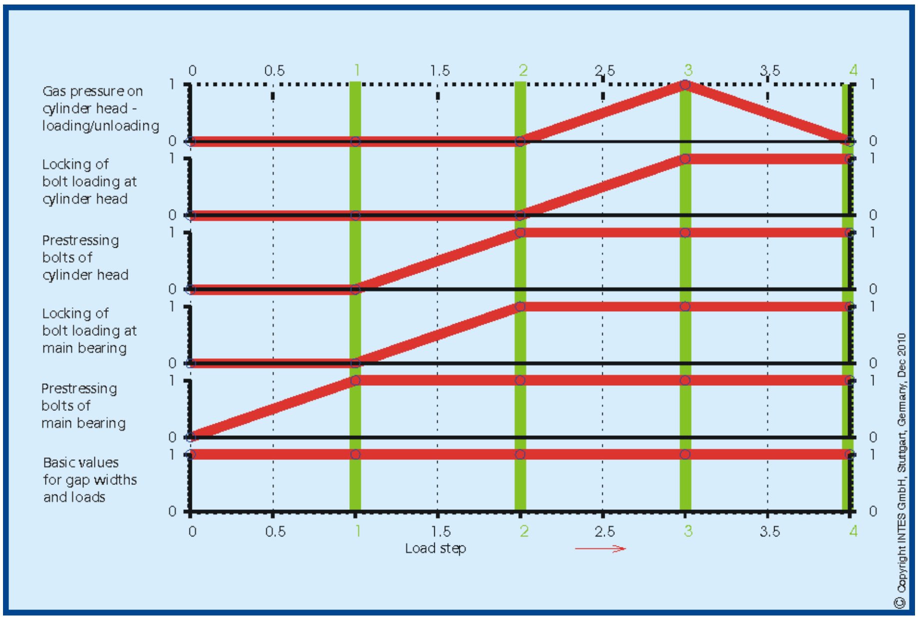

Figure 4: Plot of non-linear load history for engine analysis (example)

5: Gasket Analysis – State of the Art Algorithmic Process

The solving of gasket elements is calculated as part of the solution process for the stiffness matrix (loop of NLMATERIAL iteration). Fig. 5A shows the three main loops (CA-iteration nested in NLMATERIAL-iteration, nested in load step history) during the non-linear engine analysis.

Contact is solved iteratively for each loop of the non-linear material solution process. And both loops are several times repeated in the loop of non-linear load steps.

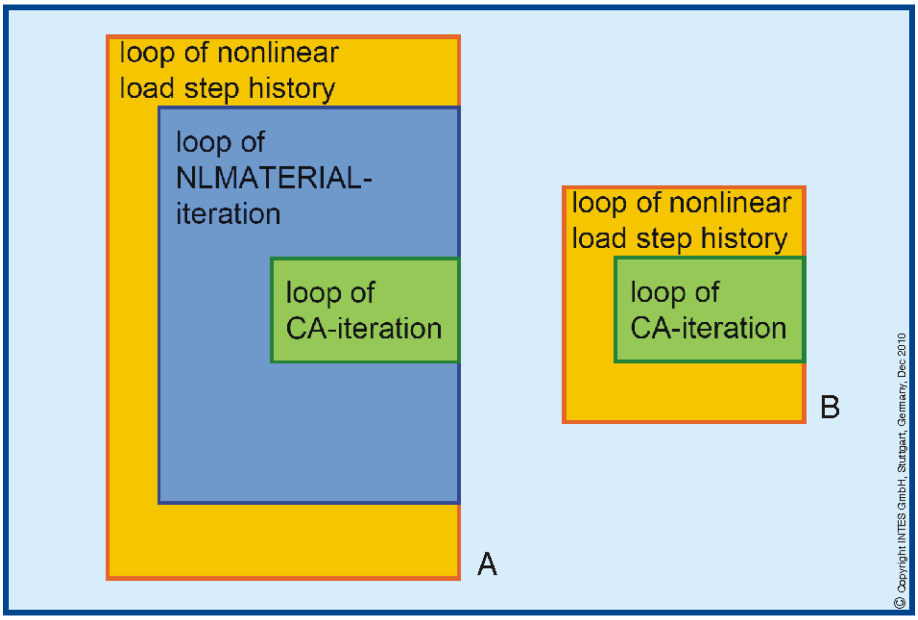

Figure 5: Analysis process with (A) and without (B) non-linear material loop

6: Non-linear Gasket Solution by Flexibility Method

In the new process the gasket element solution is shifted from the non-linear material loop to the CA-iteration. This is against the well-known rule for efficient algorithms, that it is more efficient to do the effort in the outer loops and not in the inner loops that are repeated very frequently.

But as shown in Fig. 6 the size of the flexibility matrix for engine analysis is typically more than 100 times smaller than the stiffness matrix. In addition, this perfectly fits to the very small number of gasket elements (there is only one 2D-layer gasket elements in the 3D-model).

As second factor, the pressure/closure curve can be solved very similar to the contact by highly efficient algorithms. And the solution process for non-linear materials can be stronger focused on plastic and cast iron materials.

So, engine analysis can be divided in two classes of analysis:

1. Analysis of accurate results (for comparison with measurements) by taking into account all possible nonlinearities,
2. Analysis of representative results (for relative comparisons of variants) by taking into account most important nonlinearities only.

In the second case, variants may take non-linear gasket behaviour into account but neglect non-linear material behaviour of the other structural parts.

For this case, the most time consuming loop of NLMATERIAL iteration can be omitted (Fig. 5B). So, the run time for variant analysis is reduced drastically. This is a big breakthrough in engine analysis.

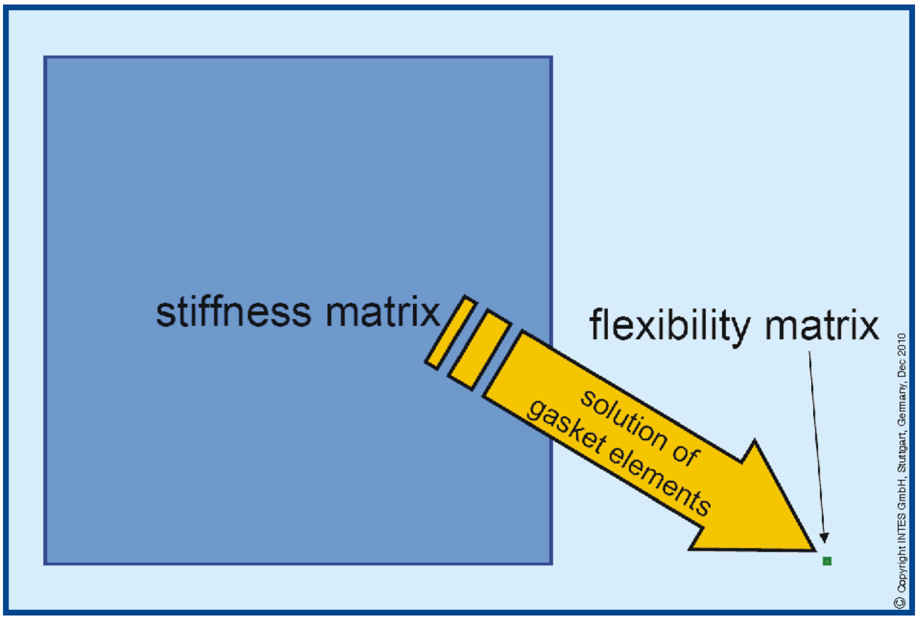

Figure 6: **Shift of matrix size for typical gasket analysis**

7: Examples

Three examples are chosen to show three different use cases for the new implemented solution algorithm. The first one shows the efficiency gain by simple switch to the new algorithm without any reduction in model quality. The second shows the big reduction that is possible for variant analysis. And the last one raises the number of degree of freedom (DOF) a lot. A new class of model is defined by this example. Here it is possible to analyze a very detailed model in short time frame on limited hardware resources with taking into account the full non-linear gasket material and a non-linear load history.

Non-linear Gasket Behaviour, Non-linear Contact, Non-linear Materials (Cast Iron, Plastic) for Complete Model

The analysis is done on 8 core hardware with usage of 26 GB main memory. Fig. 7 shows that the former already best in class analysis time (on the left side) is reduced by a factor greater than two (reduced run time shows the right bar). This is done by solving the gasket by the iterative contact algorithm without loosing any accuracy. Therefore, the name of the new algorithm is **contact controlled non-linear gasket** (**ccnlg**) **solver**.

The disk space consumption is the same as for the conventional method.

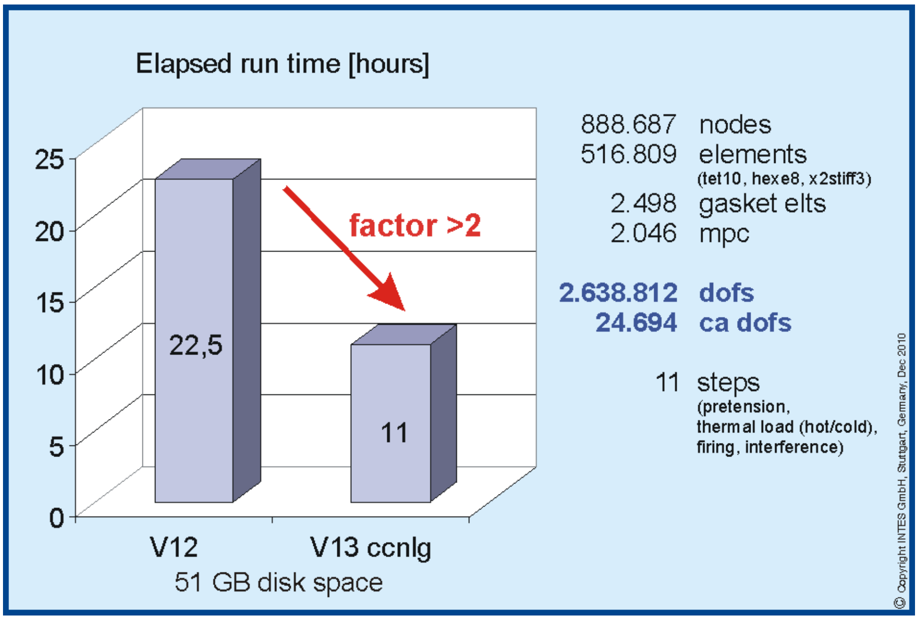

Figure 7: Engine with nonlinear materials

Non-linear Gasket Behaviour, Contact, Linear Materials for Non-Gasket Elements

The second industry engine model has more than 7.5 million DOFs and is investigated by 7 load steps (Fig. 8). All materials, besides the gasket, are linear.

Using the new solution method reduces the run time from a “several days” job by a factor of twenty to “during a longer lunch break” job. In addition the hard disc consumption is reduced from 137 GB to 87 GB (Fig. 8).

This significant reduction in analysis time makes it possible to investigate a much bigger number of variants than before. Also optimization becomes possible with the new method. Run time reduction and optimization both result in much better products.

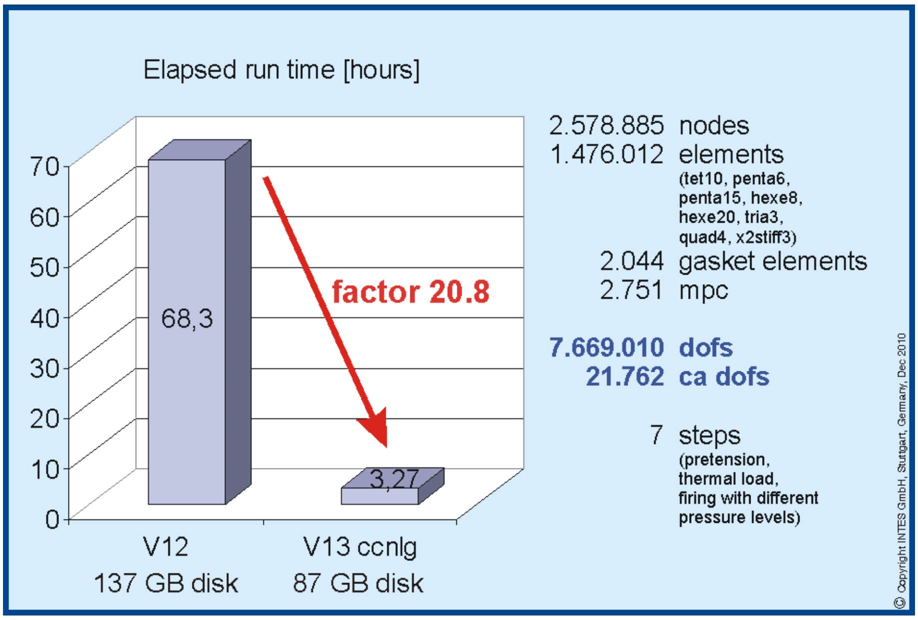

Figure 8: Engine with nonlinear gasket elements only

Big Model

In industry more accurate models are needed by means of a much finer mesh for the cylinder head. Such a model has easily close to 30 million DOF (Fig. 9). But still a load history with several steps and a full non-linear gasket with loading and unloading material data are required.

The characteristics show a formerly not solvable (on the same hardware) model, because the time and disc consumption was too high for efficient use.

Fig. 9 shows that the solution only needs a little bit more than 3 hours with the new solution method for gasket elements. This kind of model can be solved now without using expensive non standard hardware and without the need of a cluster solution.

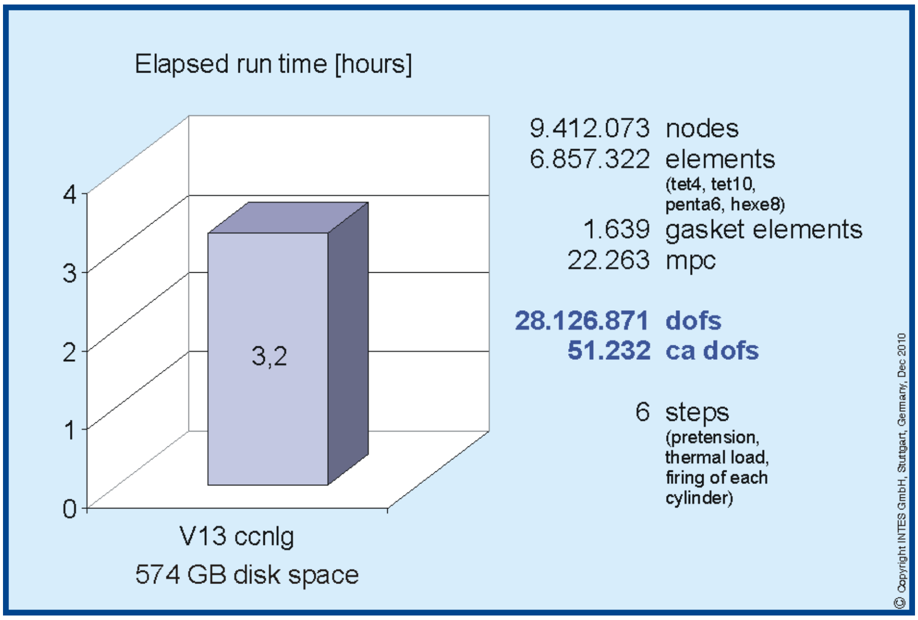

Figure 9: **Big engine model**

8: Conclusion

The new gasket solution algorithm reduces the runtime of engine analysis with non-linear gasket material to calculation times known before from simple linear analysis with contact. No additional effort for the model is needed. The full non-linear loading and unloading are included even in linear static analysis.

By the drastic reduction of calculation times which can not be delivered by current hardware evolution, new possibilities are now available. The development of engines can be improved by much finer models with more detailed results, by much more variants to get a deeper understanding of the mechanical behaviour, by optimization to improve the complex physical behaviour by an automatic process, and, last but not least, by combining bigger models, more variants, and optimization.

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