Relative Displacement in Closure Gaps due to Random Excitation – Correlating Test and Simulation Using a 3D Laser Vibrometer and the E-LINE Method

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Abstract

Relative displacement in closure gaps of a passenger car can cause chafing and abrasive wear between the exterior components close to the visible gap. Further the relative displacement can cause squeak in the sealing. In order to minimize the risk for this type of phenomena already during the virtual development phase the simulation capability has to be increased. To achieve this capability increase, a correlation in time domain between test and simulation is performed. The focus is on global damping and sealing stiffness because the relative displacement is very sensitive to these parameters.

In the SAE article 2012-01-1553 both the simulation method and the test procedure are described on a simplified model using two plates. The current article shows the application of the simulation method and the test procedure on a car body structure including tailgate, rear lamps and bumper. Three different test setups are used in order to enable the determination of the global damping value and the sealing stiffness. One test setup includes increased torsional body stiffness.

The global damping and the sealing stiffness values are determined based on the correlation in time domain according to the E-line approach. The same 8 s long pseudorandom signal is applied on the front end of the body structure for both the test and the simulation. A 3D Laser Vibrometer is used to measure the response in points on both sides along the tailgate gap. The measured and simulated displacements in time domain are used for the correlation. By using the time domain correlation approach the modal participation factors are included in the determination of the global damping value, which is also highlighted in this article. The determination of the stiffness values for the sealing considers all three directions: closing, lateral direction and along the sealing.

It is shown that the obtained damping and sealing stiffness values are clearly increasing the capability to simulate the relative displacement during the virtual development phase.

1. Introduction

Relative displacement in the closure gaps can cause chafing and abrasive wear between the exterior parts of a vehicle, as well as squeak in the sealing. At Volvo Car Corporation a simulation evaluation process called the E-line method is used to address this type of problem already during the virtual development phase. In order to increase the simulation capability a correlation in time domain is performed. The focus is on the determination of the global damping value and the sealing stiffness.

2. E-line method

The E-line method is focusing on calculating and evaluating the relative displacement between two parts, which is the main cause for Squeak & Rattle, chafing and abrasive wear. The evaluation is always performed in time domain and in a local coordinate system in order to capture the displacement in the rattle direction and in the squeak plane, see Figure 1.

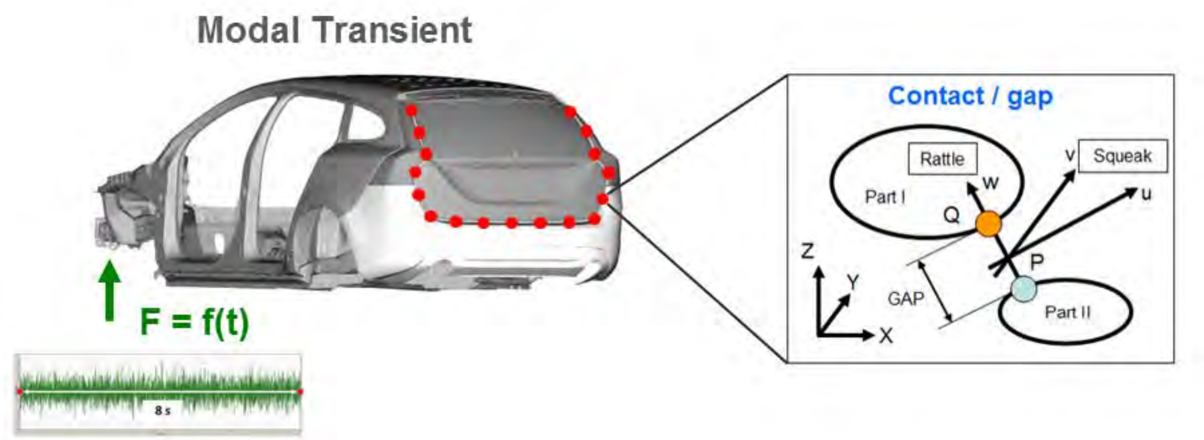

Figure 1: E-line along tailgate gap

To enable an efficient evaluation of the relative displacement, node pairs are defined along a 3D curve, which is located between the two parts. Each node pair has its own local coordinate system in order to capture the local gap geometry.

The load is defined in time domain and can come from e.g. a PSD definition or a recorded time domain data. The resulting displacements along all the E-lines are calculated in the local coordinate system belonging to each node pair. The displacements are the input to an interface in Matlab, where the evaluation can be performed on a global level, a line level and a point level [1,3].

Since the result is a response in time domain (transient) a statistical approach is needed to include the time aspect in the evaluation. The amplitudes are ranked and a certain percentage of the highest values is chosen. Finally, the mean value of these amplitudes is calculated [1]. In this way, the whole time history of the relative displacements can be condensed into one single value, which can be compared to a tolerance value for squeak or rattle assessment.

3. Correlation in time domain

The response A(t) of a modal transient analysis is the sum of all modal contributions c_i, see Figure 2. The modal contribution is the product of the eigenvector v_i and the participation factor Ψ_i.

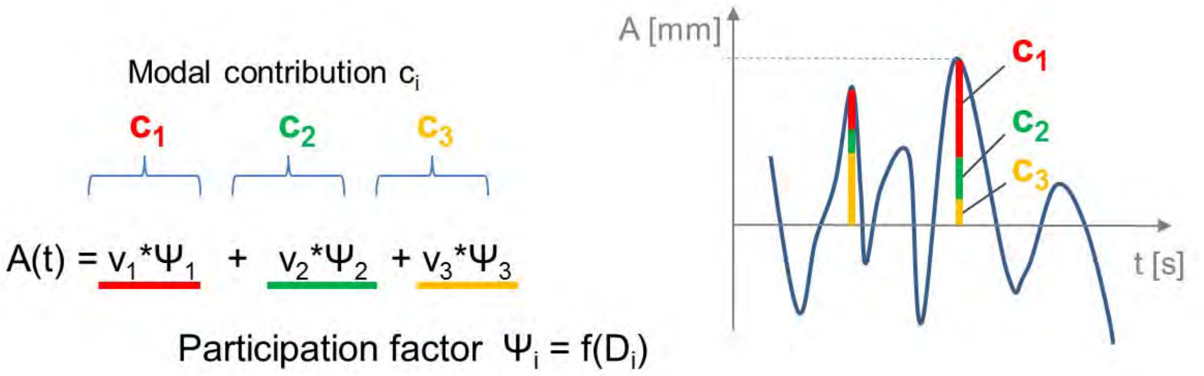

Figure 2: Response in time domain – modal contribution

A modal damping value D_i can be assigned to each modal contribution, because the participation factor is a function of the modal damping. These modal damping values can be determined e.g. through a modal correlation for a defined test setup.

When simulating a complete trimmed vehicle it is not possible to identify all modal damping values due to a large number of modes. A common approach within the simulation is to use a single damping value instead, a so called *global damping*.

The correlation in time domain is performed by comparing the test response to the simulated response using the statistical approach from the E-line method. The aim is to determine the values of global damping and sealing stiffness by minimizing the difference between test and simulation responses.

The advantage of using this time domain approach for determining the global damping value is that the participation factor is acting as a weight factor [6].

4. Test

In the test the relative displacement along the tailgate gap due to a pseudorandom excitation is measured. The test object is a BIW (“Body in White”, car body) of a Volvo V60 with tailgate, bumper and rear side lamps, see Figure 3. The 3D Laser Vibrometer is placed behind the test object to measure the response of the visible rear end [5].


Figure 3: 3D laser cameras pointing to the rear end – shaker location in the front end

The unknown parameters, global damping and sealing stiffness will be determined based on correlation studies. The correlation study is divided into two parts. The first part is the visual modal correlation that ensures the fidelity of the simulation model. The second correlation part is performed in time domain. The relative displacements in the closure gap from test and from simulation are compared. This leads to the determination of the unknown parameters.
The results from the modal test (FFT or Fast Fourier Transform run) are used to extract the mode shapes and modal damping values in LMS (Polymax).
However, the relative displacements are evaluated in time domain. The Polytec 3D Laser Vibrometer measures the response of one point at a time. Relative displacement requires the response of two points of interest at exactly the same point of time. Therefore, the trigger function is used in order to ensure that the same pseudorandom signal is applied for each single measurement point [1].
Figure 4 illustrates all defined measurement points on the test object. For the time domain measurement only the point pairs along the visible gap are of interest. In total 70 point pairs along the tailgate gap are defined to evaluate the relative displacement between the tailgate and exterior parts and to compare it with the simulation results in the E-line Matlab script.

However, for the FFT run, the response of all points (285 points in total) is used to capture the mode shapes of the test setup.

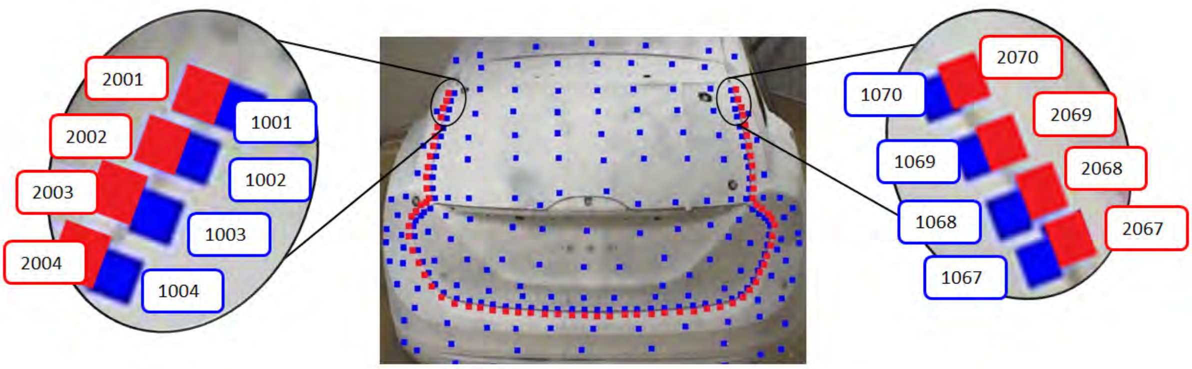

Figure 4: Defined measurement points on the test object – point pairs along the gap

There are three setups defined for the correlation study:

Test setup 1: The first test setup has no sealing mounted between the BIW and tailgate. This enables the determination of the damping value for the BIW.

Test setup 2: In the second test setup, the sealing was mounted to the BIW to include its impact on the relative displacement. Having the damping value from the first test setup limits the second setup correlation to only the sealing stiffness in all three directions.

Test setup 3: The third test setup includes a beam system mounted in the BIW to increase its torsional stiffness. The sealing is kept from the second test setup. Results from the third correlation setup aim to ensure the accuracy of the first two measurements through providing further confirmation. Moreover, it investigates the impact of increased torsional stiffness on the relative displacement.

Four air-pillows are placed under the car body to get test boundary conditions as close as possible to “free-free”. The car is painted in white by a developer flaw detection spray to increase the reflectivity for the laser beams.

An 8 s pseudorandom signal (PSD 0-200 Hz) is used for the measurement. The modal shaker applies the signal through its stinger perpendicular to the front-left side of BIW, see Figure 3.

Before the results from the time domain run can be assessed, the contribution from the rigid body modes needs to be eliminated. A high-pass filter with a cut-off frequency set to 10 Hz is used. After filtering the data, a coordinate system transformation needs to be performed. All test data is saved in the global coordinate system during measurement, but the simulation gives the relative displacement in local coordinates in each node pair [1,3].

5. Simulation

The simulation model contains the BIW, lamps, bumper and tailgate, see Figure 5. In order to bring the simulation model as close as possible to the test setup, the mass, geometry, material data and connections are thoroughly checked [2].

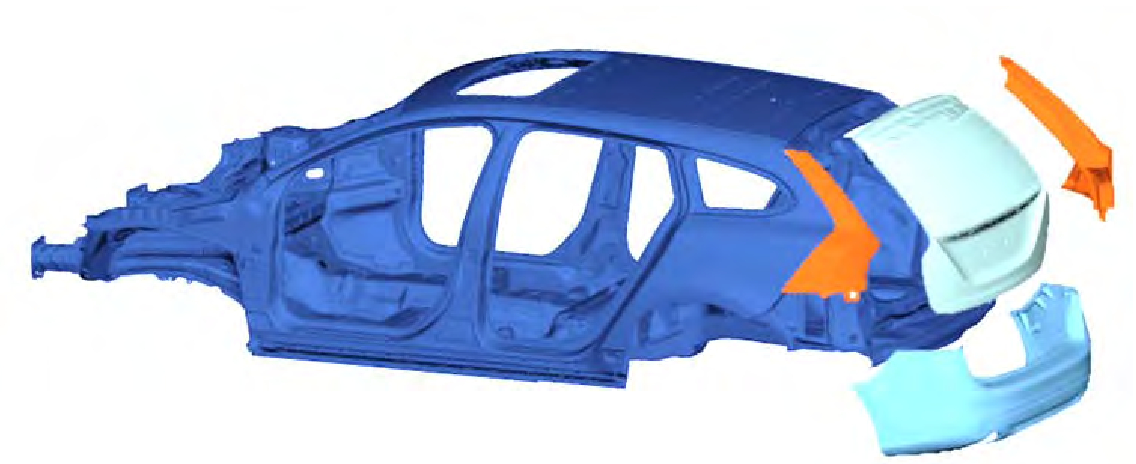

Figure 5: Simulation model

The sealing is represented by spring elements, with stiffness in three directions following the sealing gap geometry, see Figure 6. The spacing between the spring elements is 20 mm, which gives a length specific stiffness unit of N/mm/20mm for the sealing.

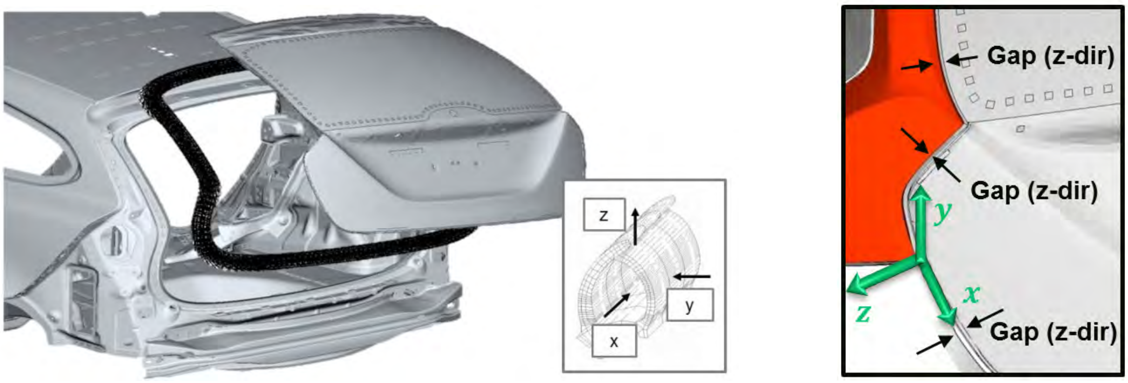

Figure 6: Sealing represented by spring elements – local gap direction

In Figure 7 the beam cross is shown, which is used for the third test setup in order to increase the torsional stiffness.

A B

Figure 7: Beam cross to increase torsional stiffness – Simulation (A) and Test (B)

In order to calculate the relative displacement in exactly the same points as in the test, all the measured points are exported from Polytec and imported into the simulation model. The E-line creation is performed by using these imported points. The local z-direction is pointing in the gap direction, see Figure 6.

A simulation in time domain is applied by using the modal transient analysis (SOL 112) in Nastran. The 8 s long measured force signal from the test is used as an excitation for the simulation. Similar to the test no boundary condition is applied (free-free).

For each of the three test setups (without sealing, with sealing, with sealing and beam cross) a simulation has been performed.

6. Correlation of test and simulation

After testing and simulating the relative displacement, the results can be compared and evaluated in the E-line Matlab script. The relative displacement is evaluated always in a local coordinate system, which belongs to each node pair along the tailgate gap. When plotting the results along the gap line a mean value of 30% of the highest relative displacement values is used in order to enable a robust evaluation of the transient response.

To choose a best fit between the test and simulation results, an error function is defined as the sum of squares of the differences. Figure 8 shows the magnitude of the relative displacement for the first setup from test (solid) and from simulation (dash/dot). The first guess for the simulation is a global damping of D=1.0% (dot). Since the damping is the only unknown parameter in setup 1, a best fit can be achieved by decreasing the value to D=0.5% (dash).

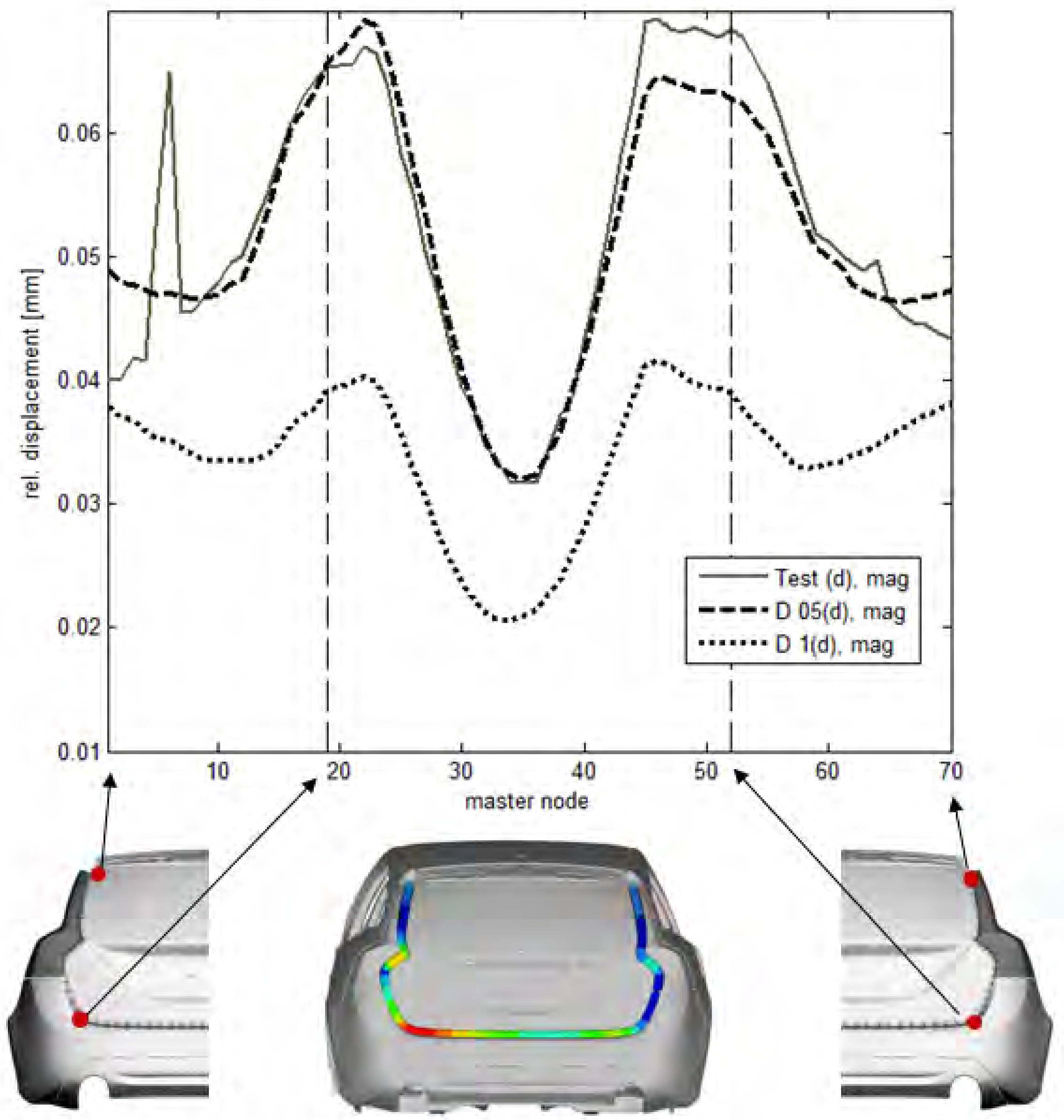

Figure 8: Comparing relative displacement between test and simulation. The relative displacement plot starts at the upper left corner and ends at the upper right.

The relative displacement for the local z direction (rattle direction) is also evaluated, see Figure 9. The dash curve is the response for the simulation and the solid is the relative displacement plot for the test. Both the shape of the curves and values show a good correlation in the local z axis, which is the gap direction.

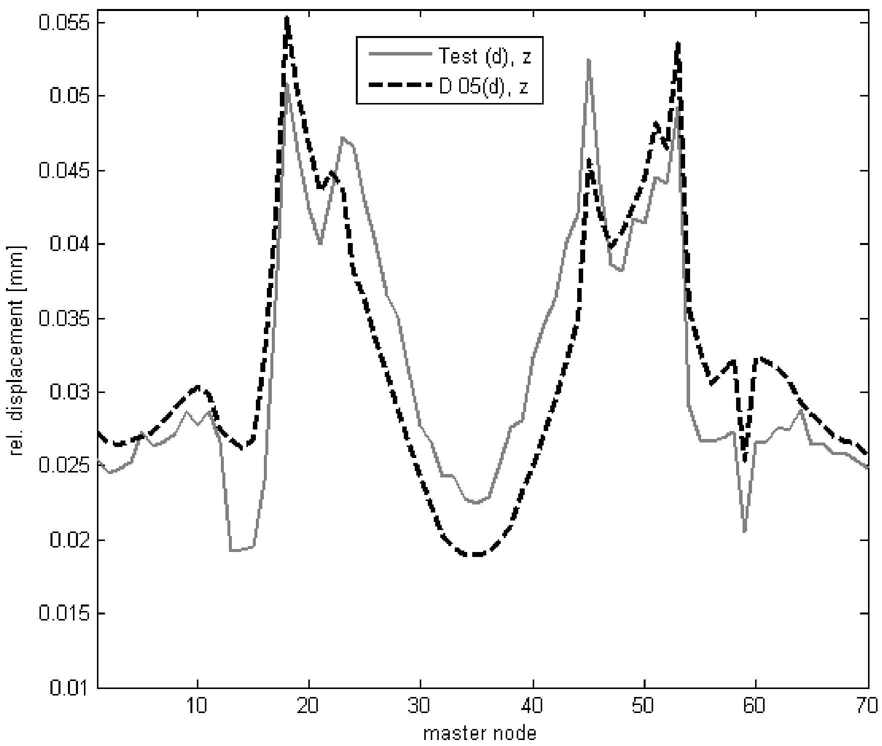

Figure 9: Relative displacement in local z direction for test and simulation (setup 1)

This good correlation is also valid for the local y ("flush", normal to the gap) and local x axes (along the gap), see Figure 10.

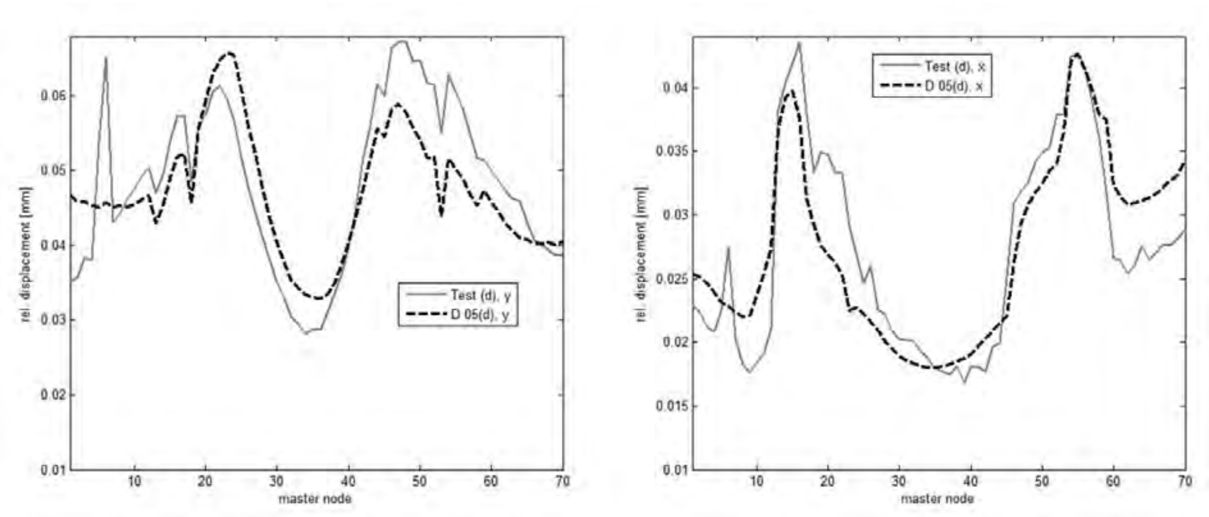

Figure 10: Relative displacement in local y and x direction for test and simulation (setup 1)

The damping of D=0.5% determined by test setup 1 is used as a given value for the correlation of setup 2 and 3.

In the second setup, the three unknown parameters are sealing stiffness in all three directions k_x, k_y and k_z. Each parameter can be varied independently in the simulation. When varying a single stiffness value the eigenmode and eigenfrequency are changed. This leads to a change in amplitude and phase during the modal transient analysis and makes a prediction by extrapolation difficult.

In order to systematically investigate the influence of different stiffness values on relative displacement, first the impact of single values (i.e. only k_x) and also the combination of two and three values are studied. Moreover, based on engineering assessment it is assumed that the stiffness along the sealing is higher than the stiffness in closing direction ($k_x > k_z$) and the stiffness in closing direction is higher than the lateral stiffness. ($k_z > k_y$).

Based on that, several stiffness combinations can be found in the sealing stiffness cube, which gives good correlation for setup 2 and 3, see Figure 11. The stiffness combination, which gives good correlation for both setups, results in the following stiffness values: k_x= 5, k_y= 0, k_z = 3 N/mm/20mm. The stiffness in lateral direction has no significant impact on the relative displacement.

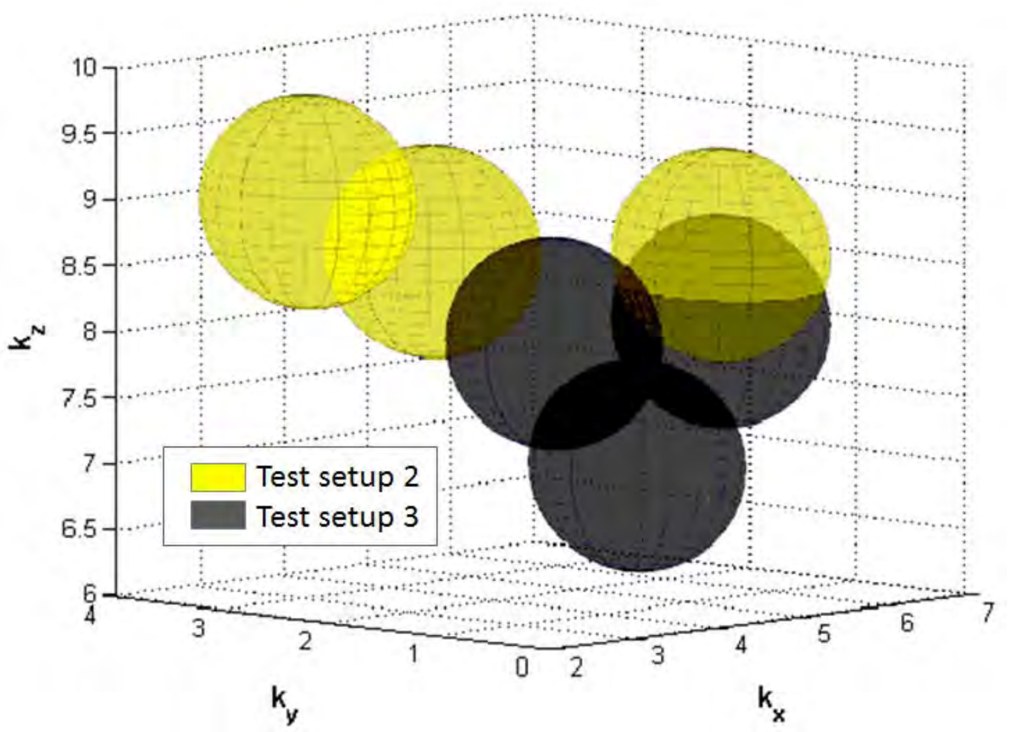

Figure 11: Sealing stiffness cube visualizing different solutions for the three stiffness values

A visual modal correlation using these stiffness values gives a further confirmation of the obtained results for setup 2 and 3.

In test setup 3 the first global torsion mode is increased by 6 Hz due to the beam cross. When comparing the relative displacement in the tailgate gap with and without the beam cross (setup 2 vs 3), it can be noted that increasing the torsional stiffness does not necessarily decrease the relative displacement along the complete gap. In some areas along the gap the relative displacement is increasing.

7. Conclusions

A correlation in time domain has been performed by testing and simulating the relative displacement in the tailgate gap of a Volvo V60. A 3D Laser Vibrometer has been used for the test. The E-line method using the modal transient analysis has been applied for the simulation. The aim was to determine the values of the sealing stiffness and the global damping. Three different setups for both the test and the simulation were defined containing the BIW (“Body in White”, car body), the tailgate, the rear lamps and the bumper. An 8 s long pseudorandom signal has been applied as an excitation in the front of the BIW.

The obtained results in time domain were compared by using the statistical approach of the E-line method. The first setup without sealing enabled the determination of the global damping value. A best curve fitting of the relative displacement along the tailgate gap between test and simulation was achieved at D=0.5%. Using this damping value, the measured relative displacement in all three local directions along the gap could be captured by the simulation. The advantage of using a correlation in time domain is the fact that the participation factors are acting as weight factors when validating the global damping.

Based on the correlation of setup 2 and 3 the three sealing stiffness values could be determined also by a best curve fitting: k_x= 5, k_y= 0, k_z = 3 N/mm/20mm.

Beside the correlation in time domain a visual modal correlation was performed for setup 2 and 3, which confirmed the obtained stiffness values.

Since the test was carried out on a BIW the obtained damping is only valid for a BIW. The simulation process requires a complete trimmed vehicle. Therefore the next step is to perform the same correlation procedure on a complete vehicle in order to determine the global damping.

Acknowledgements

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8. References

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