

## **SQUEAK&RATTLE SIMULATION AT VOLVO CAR CORPORATION USING THE E-LINE™ METHOD**

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### KEYWORDS

Squeak&Rattle (S&R), interior simulation, modal transient, stick-slip, perceived quality, dimensioning and tolerancing

### ABSTRACT

A new method for Squeak&Rattle simulation and a new approach for correlating the simulation results to real Squeak&Rattle issues have been presented in the SAE paper 2012-01-1553.

This paper focuses on the integration of this new simulation approach into an existing virtual design process. Both the technical aspect of the integration and also the organizational integration will be shown.

The technical aspect can be split into a pre- and postprocessing part. On the preprocessing side the improvement of the FE model and the load definition using test data will be described. On the postprocessing side the stick-slip test data base and the tolerance analysis will be linked to the E-LINE™ program in order to use these data as criteria for the Squeak&Rattle assessment.

By taking the capability of this new simulation approach into account the organizational integration is presented where the E-LINE™ method becomes an efficient tool to support the daily design work within both interior and exterior applications.

### TECHNICAL PAPER

#### **1. E-LINE INTRODUCTION**

The E-LINE method is focusing on calculating and evaluating the relative displacement between two parts, because the relative displacement is the main reason for Squeak&Rattle. The evaluation is always performed in time domain and in a local coordinate system in order to capture the rattle direction and the squeak plane.

To enable an efficient evaluation of the relative displacement, node pairs are defined along a 3D curve, which is located between the two parts using an Ansa script. One node is belonging to the master surface and one node to the slave surface (1,2), see Figure 1. Each node pair is using its own local coordinate system, which is aligned to the master surface. In order to capture the gap direction and the squeak plane correctly a number of different master/slave configurations are available in the Ansa script. This is an important enabler to link the E-LINE simulation results to the tolerance analysis (see chapter 4). The starting point of the E-LINE and the spacing between the evaluation points (node pairs) can be specified by the user.

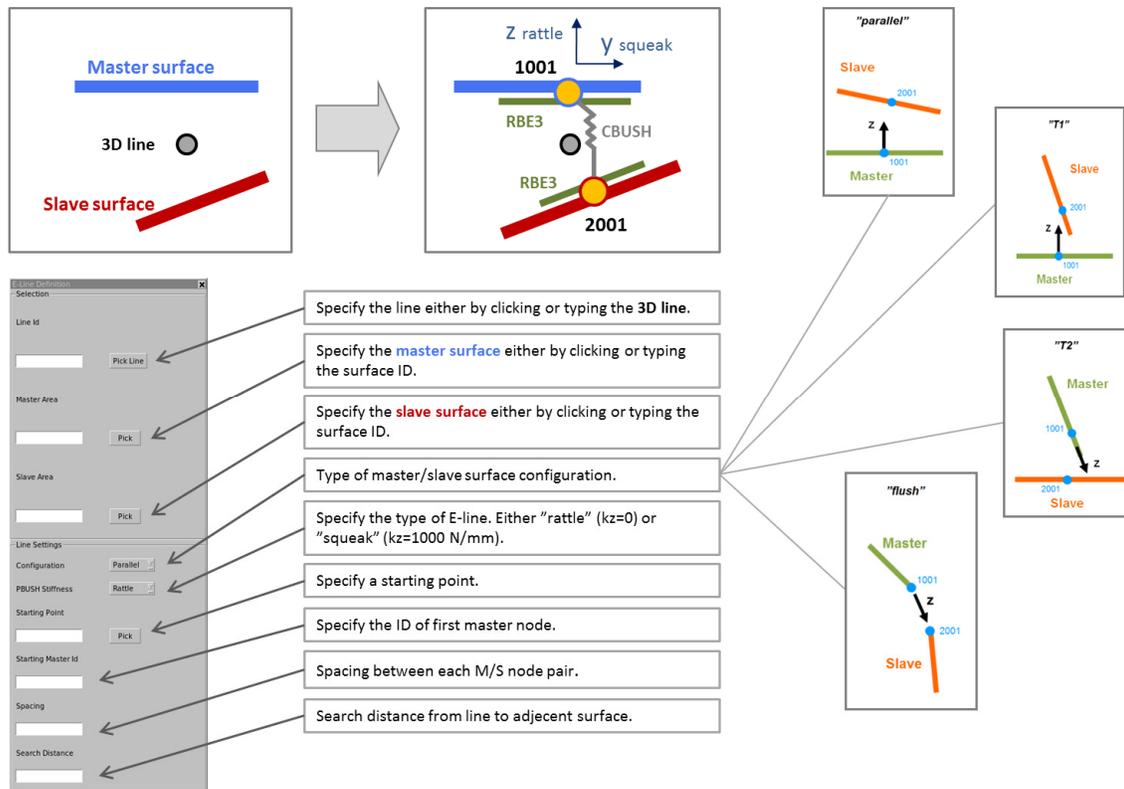


Figure 1 – E-LINE creation script in Ansa

The load is defined in time domain and can come from either a PSD definition or from recorded time domain data. The overall simulation process is shown in Figure 2. The red dotted lines are representing the E-LINES, which are created at the critical interfaces. A modal transient analysis is performed using a time signal as excitation. The displacement in local coordinates along all E-LINES is requested as output. This output is then the input to a program in Matlab, where the evaluation can be performed on a global level, a line level and a point level (2).

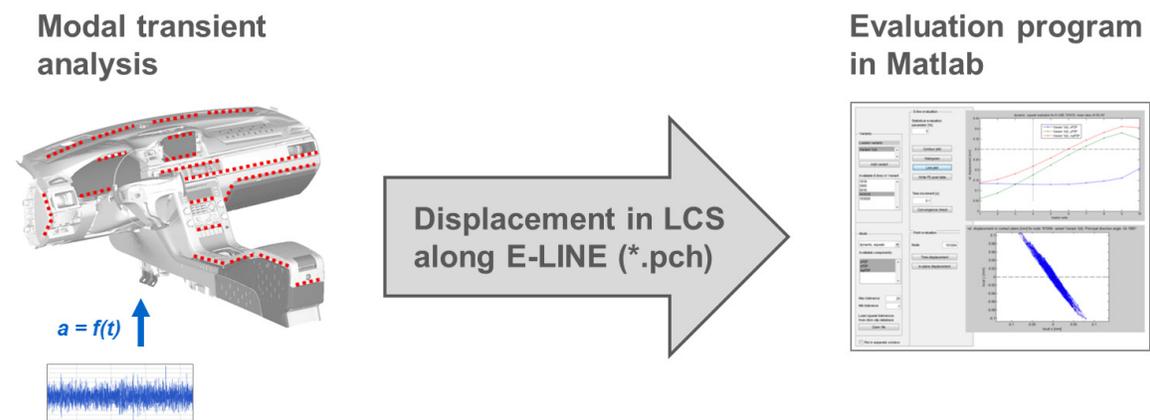


Figure 2 – E-LINE simulation process

Beside these three evaluation levels some more features of the Matlab program are shown in Figure 3.

Statistical approach

Since the result is a response in time domain due to a purely random or pseudorandom signal a statistical approach is needed to include the time aspect in the evaluation. This approach is ranking all the amplitudes and the user can choose a certain percentage of the highest values and finally the mean value of these amplitudes is calculated (2). In this way, the whole time history of relative displacement can be condensed into one single value, which is then compared to a tolerance value for squeak or rattle assessment.

Postprocessing in Meta

The results along the E-LINES can be exported to Meta in order to show them on the geometry represented by the simulation model.

Convergence check

By using the convergence check the user can identify the minimal time length required for the peak average to reach a stable value. This check is related to the statistical approach (2).

Modal composition

Since the response calculation is typically based on a modal approach, the modal composition feature can be used in order to analyse which modes are contributing most to a specific output value.

Access to stick-slip test data

The impulse rate is one output parameter of the stick-slip test, which is used for the squeak assessment. A data base with the stick-slip test results can be accessed via the Matlab evaluation program.

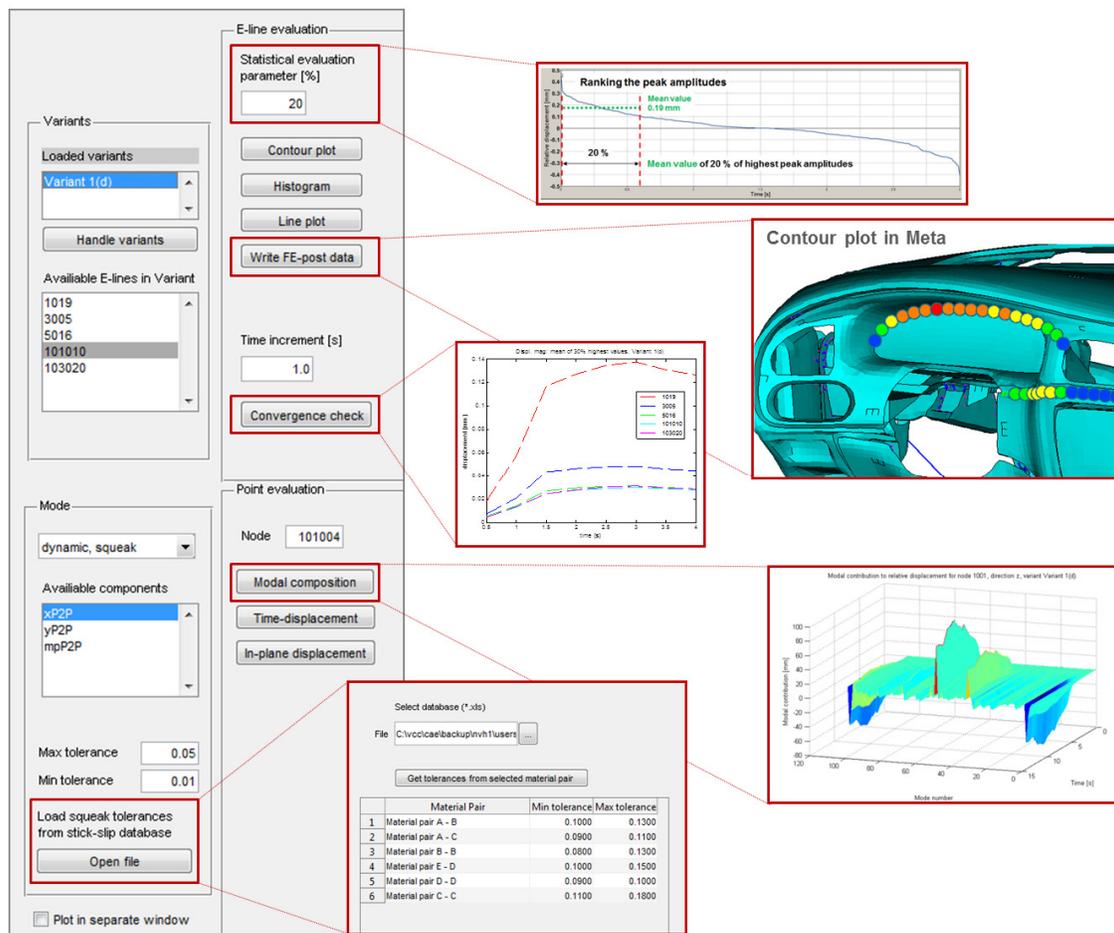


Figure 3 – E-LINE evaluation features

## 2. PROCESS INTEGRATION AT VOLVO CAR CORPORATION

When integrating this simulation method in the design process at VCC two main aspects have to be considered. The two aspects are illustrated in Figure 4.

The first aspect is a technical one, which includes both the pre- and postprocessing part of the simulation (see chapter 3 and 4). On the preprocessing side, the quality of the material data has to be improved by using the modal correlation. Also a relevant load has to be defined by using recorded acceleration data from different test tracks. On the postprocessing side, a criterion for both the squeak and the rattle assessment is needed.

The second aspect is about the integration in both the daily work and the overall design process, which consists of a virtual phase and a validation phase (see chapter 5).

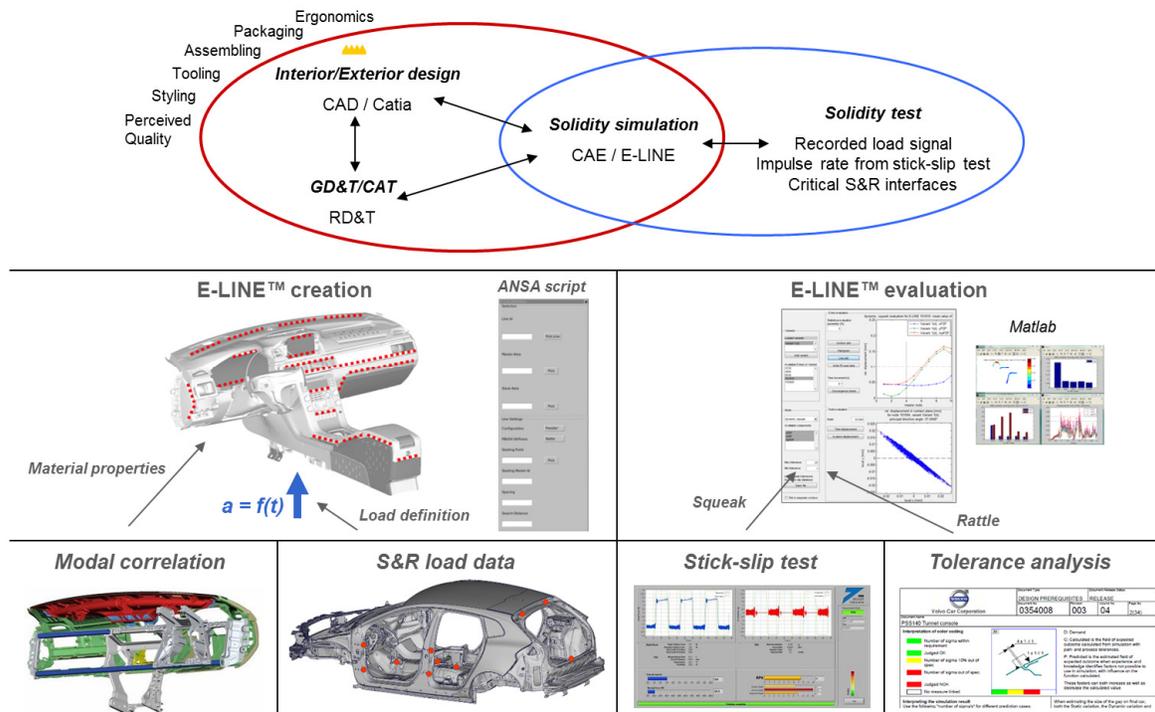


Figure 4 – E-LINE implementation at VCC

## 3. PREPROCESSING

### Improving the simulation model

The correct material data for plastic parts can be a challenging question when simulating an interior assembly like an instrument panel. A very efficient way to improve the material data is to perform a modal correlation on a part level (1,2). In Figure 5 the main carrier of an instrument panel is shown, including foam and foil represented by solid elements. The material data for foam and foil in the final part is unknown. A test setup for the part is defined, where at least three to four eigenmodes in a relevant frequency range can be clearly identified. The test is performed with a 3D Laser Vibrometer. The operating deflection shapes at resonance peaks are then visually compared to the simulated eigenmodes. Since the Young's modulus is independent of the eigenvector in this case, the Young's modulus can be updated in order to correlate the frequency, see Figure 6.

Through this procedure the material data for the main structural parts can be improved significantly.

An additional aspect of improving the simulation model is the level of detail. Since the E-LINE method has an increased focus on details, the detail level of the simulation model has to be

increased accordingly. In case of an instrument panel details like air vents, switch panels and displays have to be represented as structural parts.

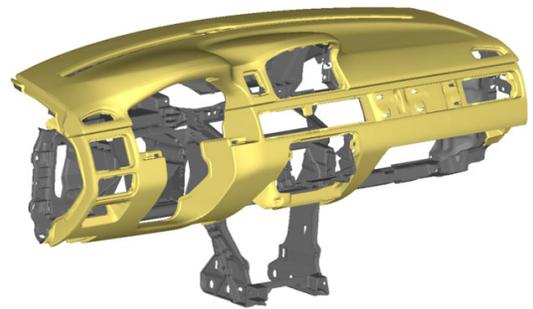
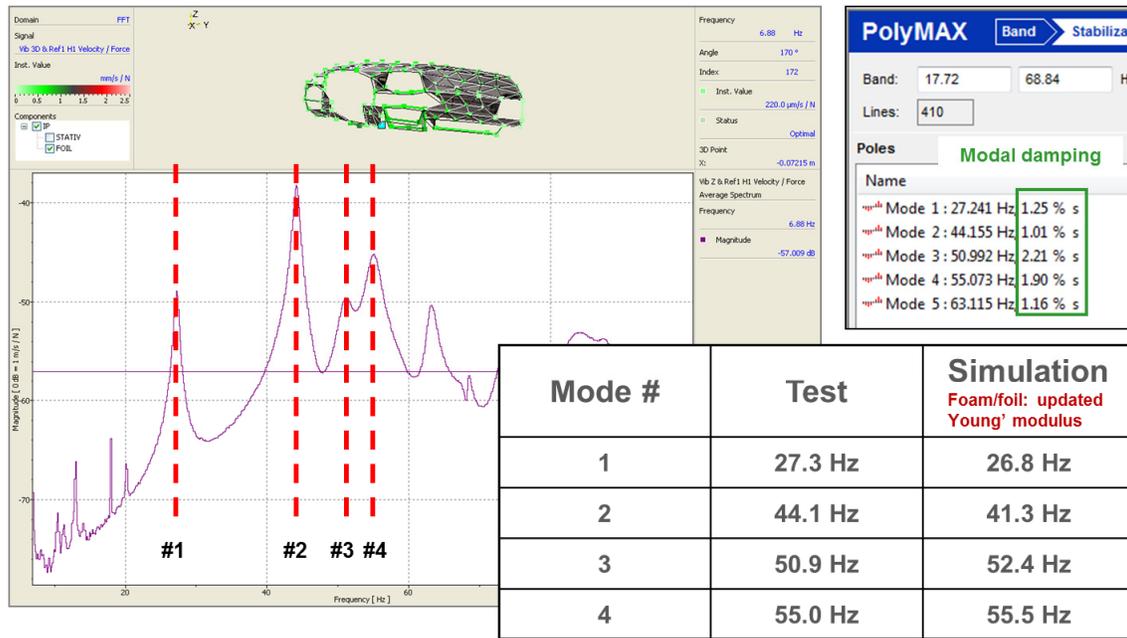


Figure 5 – Modal correlation on part level using a 3D Laser Vibrometer



**Updated material data for foam/foil**

Figure 6 – Visual mode correlation and update of Young’s modulus

Load definition

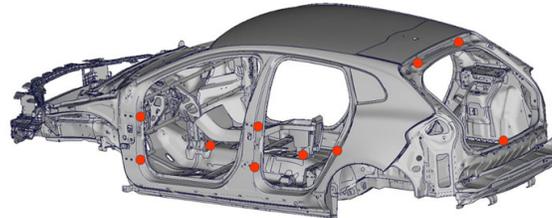
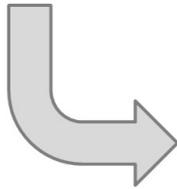
Before start of production, a Squeak&Rattle test is performed on a number of different test tracks at different velocities. The aim is to identify as many Squeak&Rattle issues as possible. This test approach based on many years of test experience and knowledge shall be adapted to the simulation approach. Therefore the acceleration at the mounting points of all main interior assemblies (cockpit, door panel, tailgate trim) is recorded on all S&R test tracks. In each mounting point, the acceleration is measured in X, Y and Z, see Figure 7. The recorded data is then converted to a TABLED1 format in order to use it as excitation for the modal transient analysis.

To support the design work during the virtual development phase in an efficient way, it is important to reduce the number of load cases. The aim is to define one “worst case” load signal for this type of simulation.

- Test track A at 40 km/h
- Test track B at 50 km/h
- Test track C at 30 km/h
- Test track D at 80 km/h
- Test track E at 100 km/h



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1	6101 x - 6102 y - 6103 z
2	6104 x - 6105 y - 6106 z
3	6107 x - 6108 y - 6109 z
4	6110 x - 6111 y - 6112 z
5	6113 x - 6114 y - 6115 z
6	6116 x - 6117 y - 6118 z
7	6119 x - 6120 y - 6121 z
8	6122 x - 6123 y - 6124 z
9	6125 x - 6126 y - 6127 z
10	6128 x - 6129 y - 6130 z
11	6131 x - 6132 y - 6133 z
12	6134 x - 6135 y - 6136 z
13	6137 x - 6138 y - 6139 z
14	6140 x - 6141 y - 6142 z
15	6143 x - 6144 y - 6145 z

Figure 7 – Recording Squeak & Rattle load data

#### 4. POST PROCESSING

##### Squeak assessment

The results of the stick-slip test are used as assessment criteria for squeak. The new parameter (Max Principal Peak to Peak) enables the comparison between the simulation results of the E-LINE method and the test results of the stick-slip machine (2).

The stick-slip test machine used at VCC is shown in Figure 8. This machine can test the stick-slip phenomenon of a material pair. One part of the pair is mounted on the carrier, where the velocity can be adjusted. The other part of the pair is mounted on the spring, where the normal force is applied and the friction force is measured. The complete test unit can also be used in a climate chamber in order to vary the temperature and humidity.



Figure 8 – Stick-slip test machine from Ziegler-Instruments GmbH used at VCC

A typical result sheet is shown in Figure 9. The red curve shows the friction force measuring the stick-slip phenomenon. For a given test setup (velocity, normal force, temperature and humidity) the impulse rate is one output parameter. The impulse rate is the number of pulses (single stick-slip) per mm relative displacement.

By inverting the impulse rate, the delta relative displacement is defined, which is needed to create a single pulse. This value is compared to the Max Principal Peak to Peak amplitude (Max Principal P2P) to perform the squeak assessment (2). As long as the “1/impulse rate” value is below the Max Principal P2P, there is no risk for squeak. If this value is above the Max Principal P2P, then there can be a risk for squeak.

To capture at least partly the real conditions in a car, the same material pair is tested in different test setups. The main focus is generally on varying the relative velocity and the normal force. The number of different test setups results in a number of different values for the impulse rate. Using this data a min and a max “1/impulse rate” value can be defined.

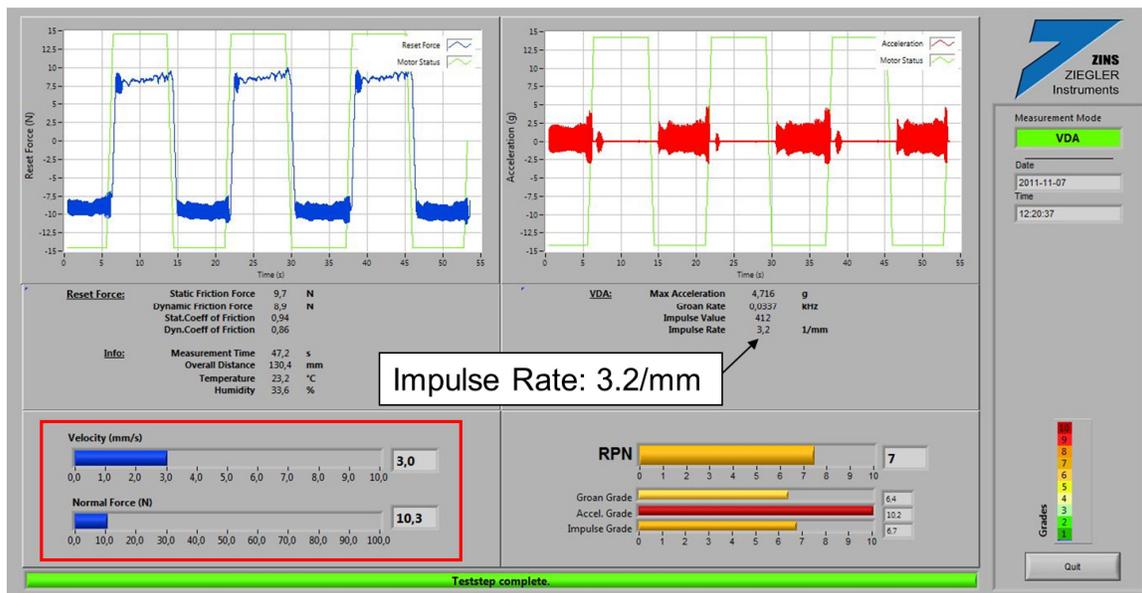


Figure 9 – Result sheet from stick-slip test machine

This min and max value can be then accessed in the Matlab evaluation program by choosing the material pair (see Chapter 1). The values are automatically plotted in the different evaluation features. In Figure 10, a histogram plot is shown. In this type of histogram the max value for each E-LINE is plotted. Additionally the results of a base version are compared to a variant.

By adding the min and max value (1/impulse rate) from the stick-slip test, all the E-LINES, which are below the min values, can be easily identified. Along these lines there is no risk for squeak. The E-LINES, which are above the max value, have definitely a risk for squeak. For squeak simulation, not only the dynamic excitation (time acceleration signal) can be used, but also the results from a static analysis (using force or temperature as load).

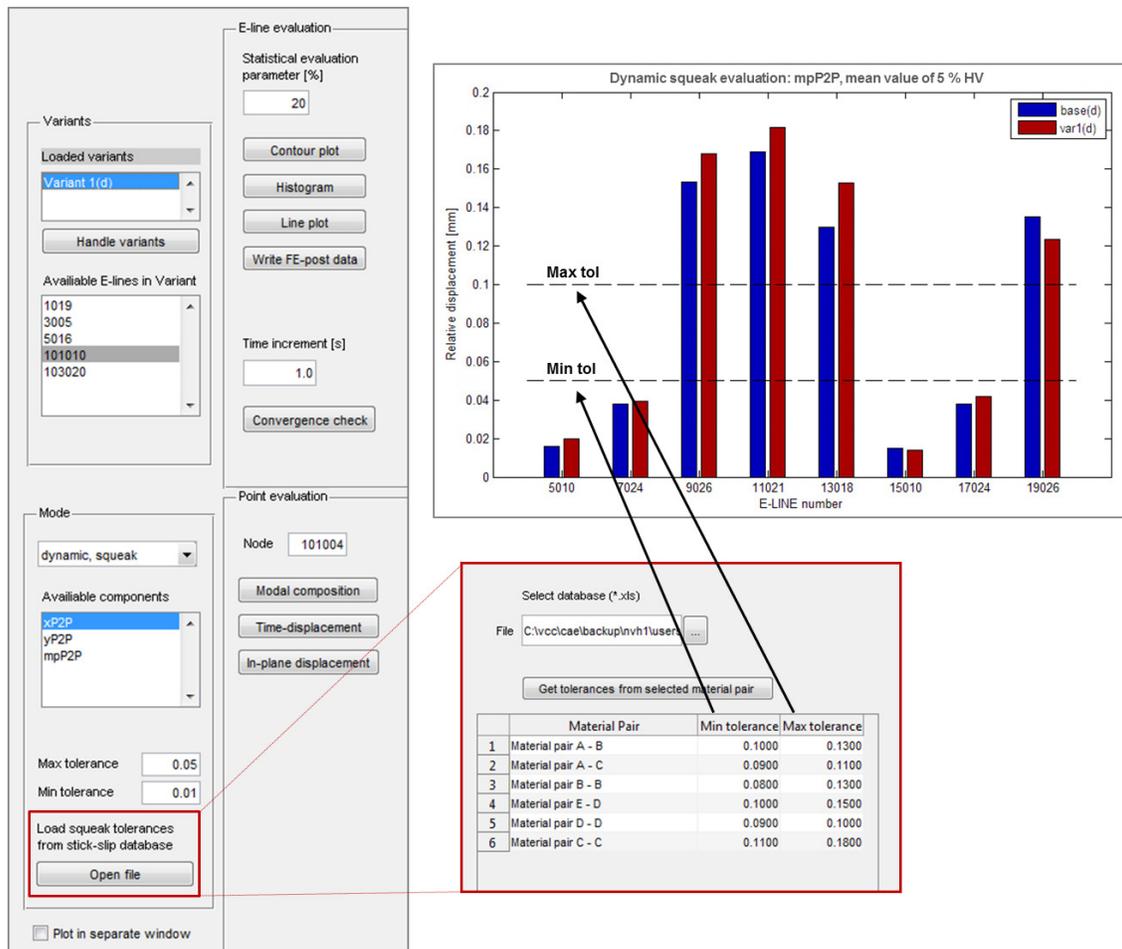


Figure 10 – Using stick-slip test results for squeak assessment

### Rattle assessment

Risk for rattle occurs when the dynamic movement between two components is larger than the defined nominal gap. In order to get assessment criteria for the rattle, static tolerances have to be considered, because they will contribute to different gaps on different manufactured units. To consider static tolerances for the whole population, results from variation simulation are used as input to the E-LINE simulation.

Perceived Quality (PQ) geometry requirements are defined for each visible split-line on the vehicle. Those requirements contain a nominal value and allow variation around the nominal

value. At VCC, variation is predicted using the Computer Aided Tolerance (CAT) tool RD&T. The overall process is shown in Figure 11. For each component in the simulation, locating schemes are defined that represent the positioning of components during assembling. Tolerances based on either measurement data from the manufacturing process or standard distributions are applied in all locating points in the locating scheme to represent assembly variation. Tolerances are also applied on each component to define part deviations. Finally, measurements are defined in all interfaces for gap and flush direction. Defined measurements represent the actual section, where the output variation is calculated. Variation is predicted using Monte Carlo based variation simulation (3). Simulation can be either rigid or non-rigid. In case of non-rigid simulation the method of influence coefficient is used (4). For each defined measurement, resulting out-put variation is represented as distribution and 6-sigma is used to define the value of maximum and minimum variation. This value is used in the assessment criteria for rattle and is here referred to as static tolerances.

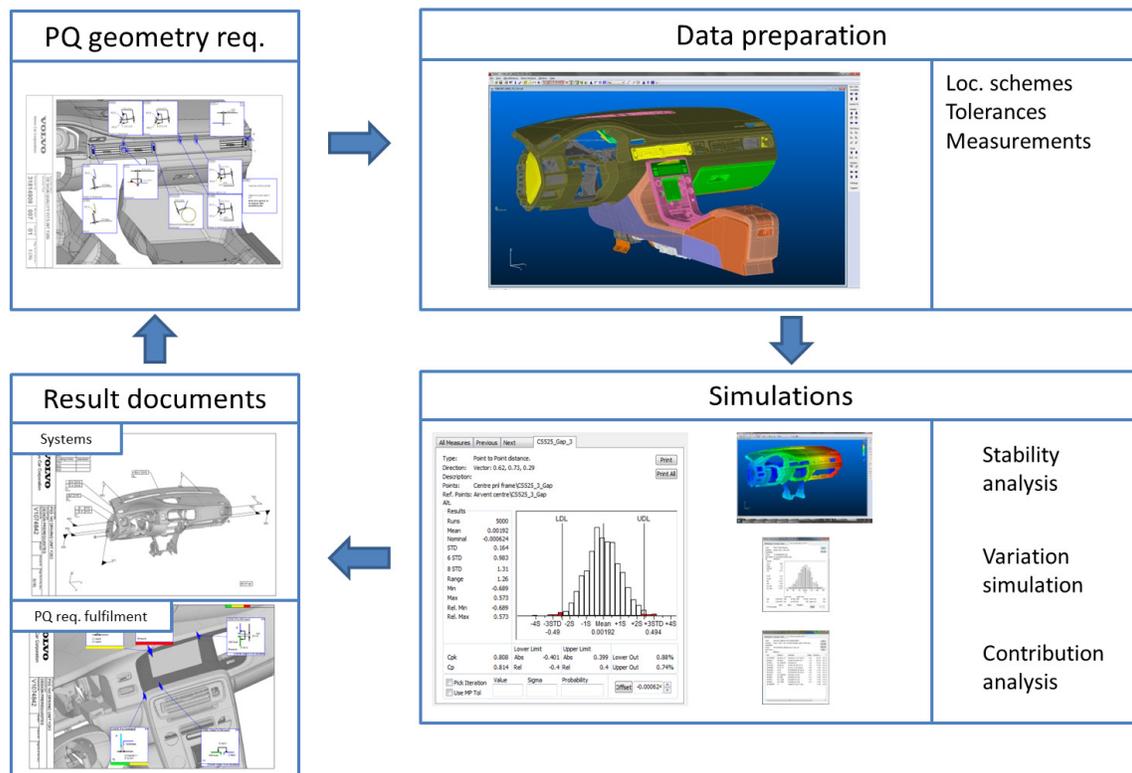


Figure 11 – Tolerance analysis in RD&T

One important aspect is that the static tolerance direction is aligned with the dynamic tolerance direction in the E-LINE simulation in order to enable the superposition of the two values. In Figure 12, a section of a gap between two trim panels of a tunnel console is illustrated. On the left hand side, the gap direction is shown, which corresponds to the direction of the output variation in the static tolerance simulation. On the right hand side the mesh from the E-LINE model is shown. The gap direction is then used as input to the E-LINE creation script in Ansa to define the local z-direction along the E-LINE, which is the rattle direction.

By this the rattle assessment becomes straight forward. As long as the dynamic tolerances are not closing the minimal static gap, there is of course no risk for rattle, but as soon as the dynamic tolerances are closing the minimal static gap, there is a risk for rattle.

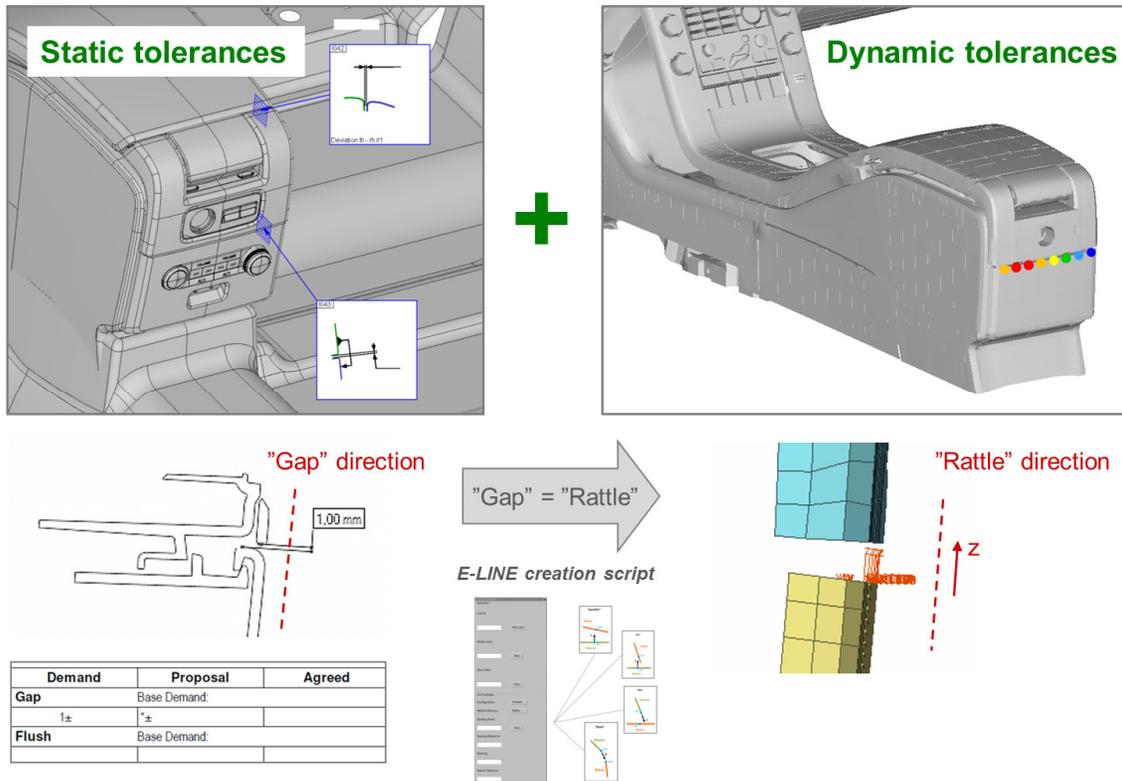


Figure 12 – Alignment of static tolerance and “rattle” direction

Ongoing development - Improving the rattle assessment

Since the E-LINE model is mesh based, it is not always possible to find a correct normal direction that is aligned with the gap direction. In Figure 13, it can be seen that the normal direction for each LCS follows the direction of the elements in the mesh and not the geometry that the mesh is based on. This means that the superposition of static and dynamic tolerances will deviate from the correct result.

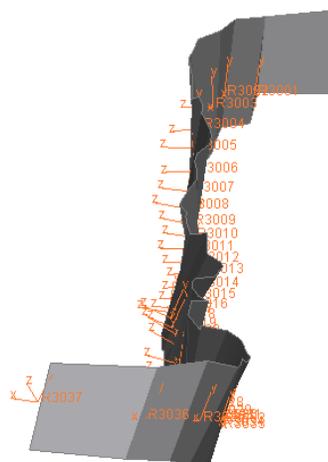


Figure 13 – Mesh based normal direction along E-LINE

In order to secure alignment between the gap direction and the rattle direction this information is defined in the CAT tool and exported to the E-LINE script. The main idea is to create the curve, which represents the E-LINE, directly in the variation simulation model.

Since it is necessary to define measurements between components in RD&T, those can be replaced by a curve that contains a number of local coordinate systems that each one defines a measurement. This function is defined as a seam in RD&T. The seam is placed between the components and the shortest distance between the components defines the direction of the measurements and also the z-direction of the E-LINE. In Figure 14, a seam between centre stack frame and air vent is illustrated. Local coordinate systems with gap direction and interface name are now exported from RD&T to be used as input for the Ansa E-LINE creation script. The seam is also used as measurement for the variation simulation in RD&T. By this the alignment between gap and rattle direction can be secured.

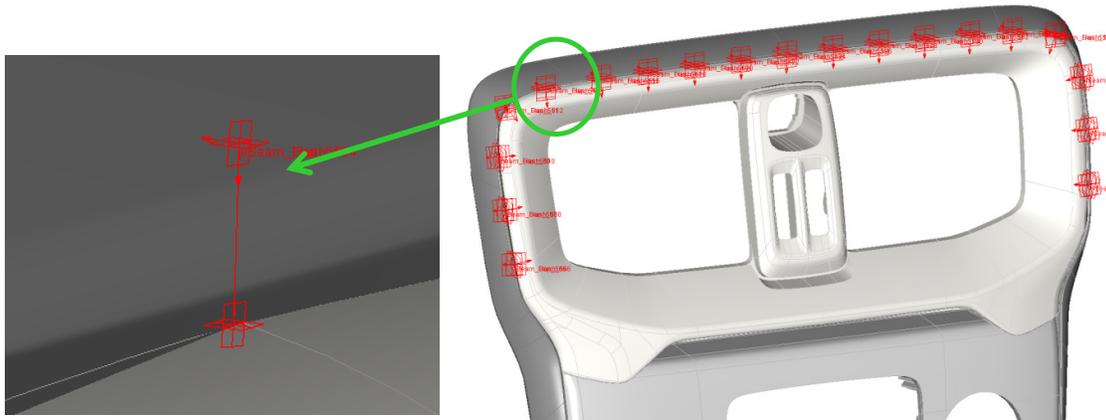


Figure 14 – Seam created in RD&T, that is exported to ANSA E-LINE creation script

In analogy with the procedure for squeak assessment, static tolerance data are now imported from RD&T to the Matlab evaluation program in order to perform the rattle assessment.

## 5. CONCURRENT ENGINEERING

### Process integration

The E-LINE method enables squeak and rattle simulations to be integrated as a standard CAE delivery in the design process. In Figure 15, a schematic design process is illustrated. The process has a virtual part that consist of a Concept Phase and a CAD Phase and a physical part, defined as Production Phase, where tools are manufactured and physical test series are built. During the Concept Phase requirements are set, styling is developed and systems solutions are chosen. In the CAD Phase, detailed design is developed. It is during this phase that the digital models have the correct maturity in order to perform FEM based simulations.

Traditionally, squeak and rattle are verified during physical built, which usually results in both late changes and cost adding solutions on the product. This is illustrated with the red activities in Figure 15. Knowledge based analysis of CAD models can be performed by experienced engineers in order to predict interfaces where S&R might occur. But this is of course not a very confident method. The traditional way of working also implies a sequential work procedure, where the design first is developed and later on, the occurrence of S&R is evaluated during physical phase.

By implementing the E-LINE method, it is possible to not only verify the occurrence of S&R during the virtual part of the design process, but also to optimize and change the design to avoid S&R issues. All E-LINE activities are illustrated with green boxes in Figure 15. During the Concept Phase, when PQ geometry requirements are set for all visible split-lines, S&R checks are performed. All activities related to PQ geometry requirements and variation

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simulation are illustrated with blue boxes in Figure 15 and are denoted CAT (Computer Aided Tolerancing). The aim is to identify all interfaces, which have a risk for S&R. Requirements that imply contact condition in nominal set up are clearly relevant for squeak evaluation. If nominal gap can be closed or almost closed by required tolerance the requirement is critical for rattle. The aim is that all requirements that imply risk for S&R shall be marked as critical already in the PQ document. When requirements are imported to the variation simulation model, all E-LINE prerequisites (LCS and directions) shall be generated for all those critical relations. This is illustrated in the Figure 15 as *Critical interfaces* and this information is transferred between E-LINE activities and CAT activities.

Before CAD data is available, the work to improve material data can be started. This is done by modal correlation on part level, which is described in section 3. Virtual and physical data from previous programs can be used for this activity.

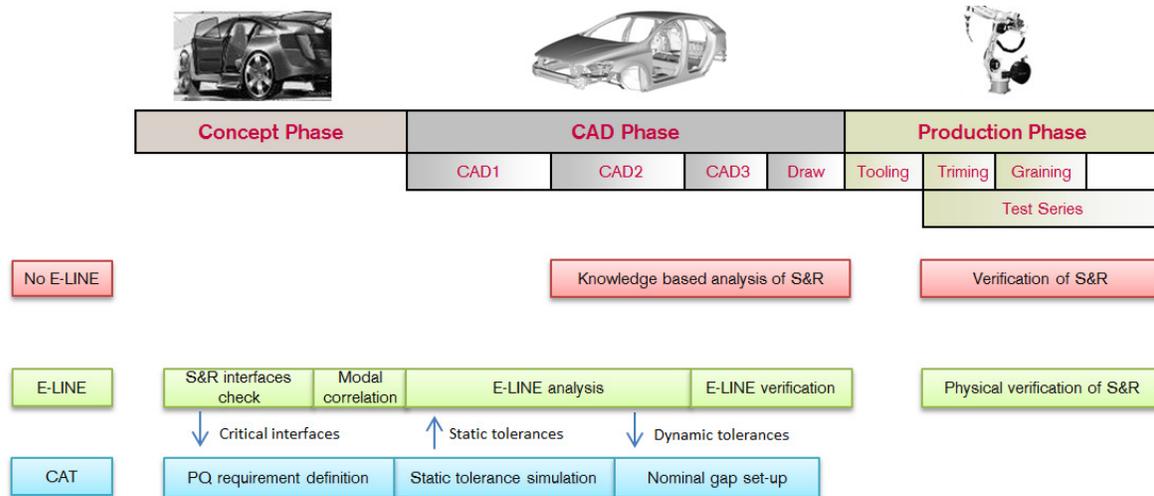


Figure 15 – E-LINE integration in a generic design process

E-LINE simulations can be started in the CAD Phase. The most important difference, compared to the traditional work procedure, is that E-LINE analysis can be used to understand and change the design in order to avoid issues. Different concepts can now be evaluated with respect to relative displacement and thereby risk for S&R. In the late part of the CAD Phase, final verification is performed on final data that is used for tooling. As seen in Figure 15, static tolerances are used as input for E-LINE analysis. Now, when the relative displacement is calculated for critical interfaces, it can be used as input for the nominal gap set-up.

Physical tests are still performed during the Production Phase and S&R will be verified physically on test tracks. The aim of the E-LINE simulation is of course to reduce the numbers of S&R issues. Now E-LINE also can be used for root-cause analysis. Implementation of E-LINE simulations enables an enhanced level of concurrent engineering throughout all parts of the design process because requirement setting, design development and evaluation of S&R now can be carried out in parallel with other disciplines.

### Daily work

Squeak and rattle simulations have many stakeholders in the organization, see Figure 16. Some are customers to the results and some contribute with input for the E-LINE simulation. When using this type of simulation, it is essential to work close together with the S&R test people. They have a lot of experience regarding the load signals, they do the stick-slip testing and they know from their test experience the critical interfaces, where E-LINE simulations shall be performed.

To the tolerance people there is almost a mathematical link based on the superposition of the static and dynamic tolerances, as described above. Static tolerances are important input for the rattle criteria and the dynamic tolerance gained from the E-LINE simulation is an important contributor to the nominal set up of interfaces.

The most important customer is of course the interior and exterior design engineers. As seen in Figure 16, design engineering have to consider all aspects of the product such as ergonomics, packaging, styling etc. It is important to consider that the S&R is just one aspect among many others when balancing a product. Design engineering knows best, where it is feasible to put an extra reinforcement, screw or clip. Now when the E-LINE method has been implemented, it is possible to support design engineering with evaluations of different concepts regarding relative displacement and to conclude, how it will affect the squeak and rattle performance.

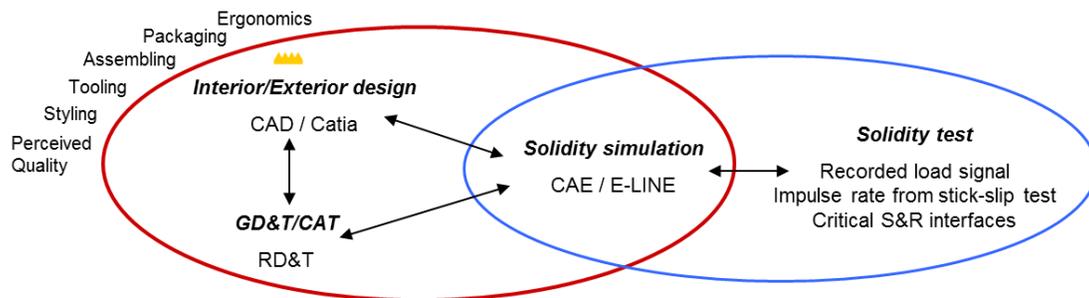


Figure 16 – Integration in the daily work

## 6. CASE

In Figure 17 the interface between the display and the bezel is shown. In order to minimize the gap size due to styling and perceived quality reasons the relative displacement due to dynamic road loads is of interest. In this case, the relative displacement normal to the display is simulated and compared to the static tolerance analysis performed in RD&T.

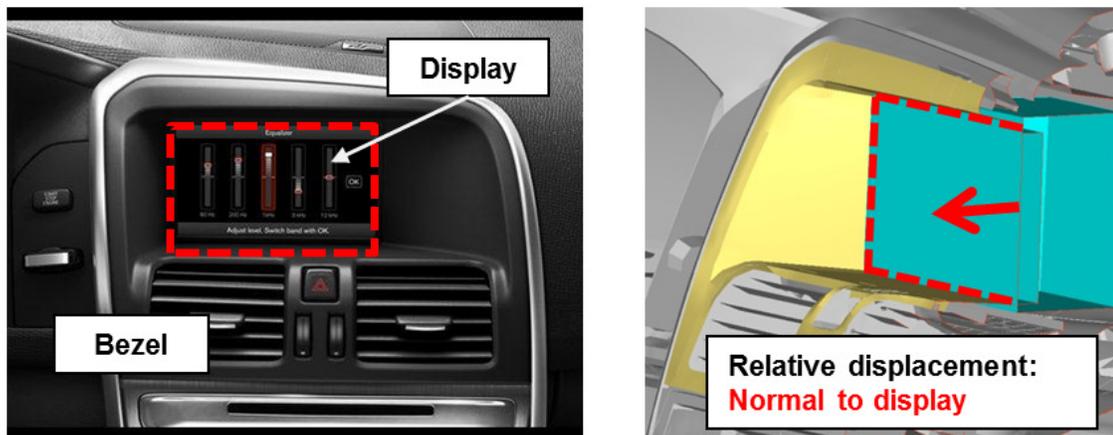


Figure 17 – E-LINE definition between bezel and display

Figure 18 shows a line plot. The components x, y, z and the magnitude of the simulated relative displacement are plotted along the E-LINE 1029, starting at node number 1001 and ending at node number 1029. Each value is evaluated in its local coordinate system, which means in the local z-direction, which is always normal to the display. These calculated results are now input to the Perceived Quality process shown in Figure 11.

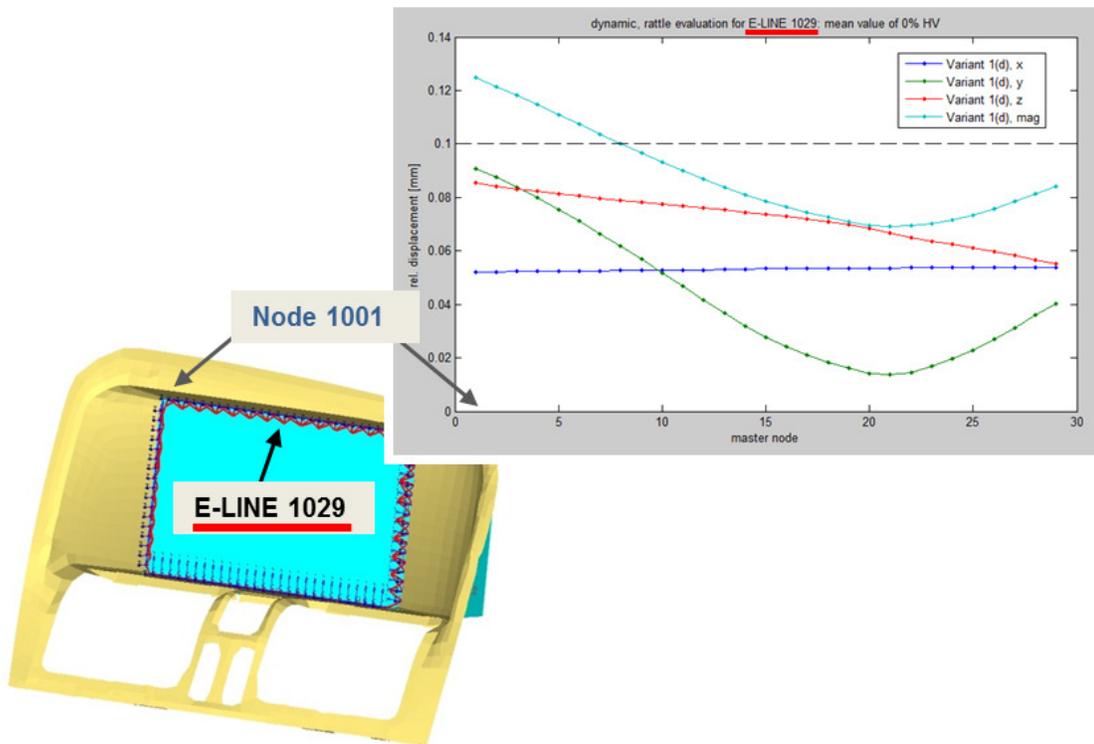


Figure 18 – E-LINE plot

## 7. CONCLUSION

This paper focuses on the integration of a new Squeak&Rattle simulation approach (2), called E-LINE™, into an existing virtual design process at Volvo Car Corporation. Both the technical aspect of the integration and also the organizational integration has been shown. The technical aspect is on the preprocessing side about improving the FE model and defining relevant load data. On the postprocessing side the stick-slip test data base and the tolerance analysis (RD&T) have been linked to the E-LINE™ program in order to use these data as criteria for the Squeak&Rattle assessment. By taking the capability of this new simulation approach into account the organizational integration is presented where the E-LINE™ method becomes an efficient tool to support the daily design work within both interior and exterior applications. Additionally, the method enables a concurrent engineering process and by creating an interface between RD&T and the E-LINE method an area for potential improvement has been identified.

## REFERENCES

- (1) Weber, J. and Benhayoun, I., "Squeak & Rattle Simulation – A Success Enabler in the Development of the New Saab 9-5 Cockpit without Prototype Hardware", *SAE Int. J. Passeng. Cars – Mech. Syst.* 3(1):936-947, 2010, doi:[10.4271/2010-01-1423](https://doi.org/10.4271/2010-01-1423).
- (2) Weber, J. and Benhayoun, I., "Squeak & Rattle Correlation in Time Domain using the SAR-LINE™ Method", *SAE Int. J. Passeng. Cars – Mech. Syst.* 5(2):2012, doi:[10.4271/2012-01-1553](https://doi.org/10.4271/2012-01-1553).
- (3) Shan, A., Roth, R. N. and Wilson, R. J., 1999, "A new approach to statistical geometrical tolerance analysis", *Int. J. of Adv. Man. Technol.*, 15(3), 222–230.
- (4) Liu, S. C. and Hu, S. J., 1997, "Variation Simulation for Deformable Sheet Metal Assemblies Using Finite Element Methods", *Journal of Manufacturing Science and Engineering*, ISSN 1087-1357, 1997, Volume 119, Number 3, p. 368

- (5) RD&T version 3.94, Copyright © RD&T Technology AB 2012
- (6) ANSA version 13.2.1 User's Guide, BETA CAE Systems S.A., 2011
- (7)  $\mu$ ETA PostProcessor version 14.1.1. User's Guide, BETA CAE Systems S.A., 2013