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## NUMERICAL SIMULATION OF SHOCK LOADS FOR HIGH-VOLTAGE TRACTION BATTERIES

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**Abstract.** In this paper, two different methods for the simulation of shock loads for high-voltage batteries are investigated. First, a test body is designed that allows the excitation of different eigenfrequencies, and dynamic measurements are performed on an electrodynamic shaker. Thereupon a simple simulation method based on a single-mass oscillator using MATLAB for the integration of motion equations is introduced. Finally, the test body is analyzed using FEM simulation. The results show that there is a good agreement between experiment and FEM simulation comparing absolute values of maximum acceleration response. The use of single-mass oscillators is imprecise for the determination of absolute values. When comparing normalized acceleration response, a good agreement is achieved for both methods.

**Keywords:** high-voltage battery, shock loads, shock response

### 1. INTRODUCTION

High-voltage batteries for electric vehicles are subject to significant mechanical loads during operation (Volk, 2018). The mechanical loads arise when driving over unevenness in the road surface, see Fig. 1 a). The mechanical loads are usually applied together with electrical and thermal loads during testing of batteries on electrodynamic shakers like shown in Fig. 1 b).

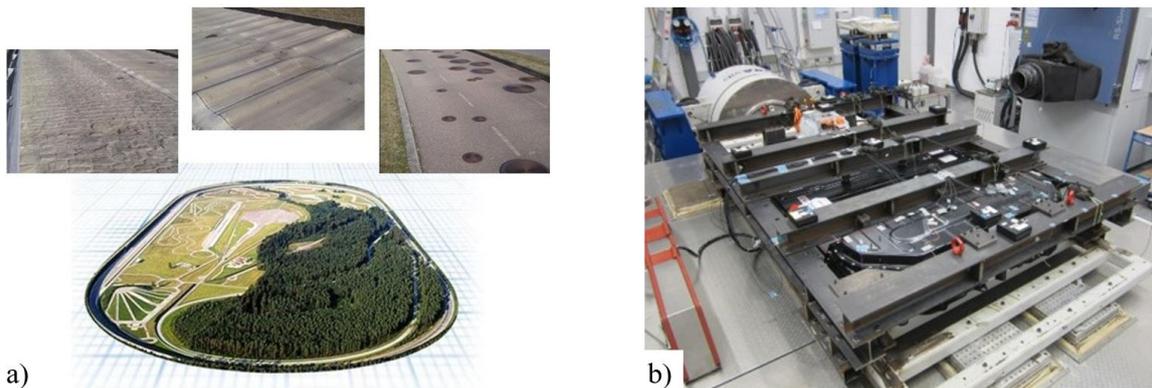


Figure 1. a) Test tracks for vehicles (image source: Volkswagen Group); b) High-voltage traction battery during testing on an electrodynamic shaker (image source: AUDI AG)

The mechanical loads are usually classified in operational loads and special or misuse load (Köhler *et al.*, 2018). The operational loads occur very often during service and are characterized by moderate amplitudes. The special loads occur, for example, when driving over potholes or curbs, and their frequency is much lower but their damage content is significantly higher. During the development of high-voltage batteries, both types of loads are taken into account at a very early stage by means of simulation (Dörnhöfer, 2018). Simulation is usually carried out using the so-called multi-level approach, in which both individual components and the entire battery are considered step-by-step (Wang *et al.*, 2017; Kutka *et al.*, 2018). The present work deals with the simulation of misuse loads, also called shock loads. Shock signals are usually described using synthetic load-time histories represented by the shock shape, duration, and maximum shock level based on acceleration.

Since shocks are the highest mechanical loads, they can have a significant influence on the integrity and the degradation of high-voltage batteries (Brand *et al.*, 2015; Hua and Thomas, 2021). Different methods can be used for the simulation of the shock response. The simplest possibility is the use of a single-mass oscillator, which can be calculated, for example, using Matlab for arbitrary shock-time histories. The advantage of this method is the very short computation times. Therefore, this method is often used to compare different load histories and to develop knowledge about the severity of different load histories.

In this work, a comparison is made between simulation and experiment for a specific body which allows a simultaneous excitation of several eigenfrequencies independently from each other. In the first step, experimental investigations are carried out in order to obtain eigenfrequencies and damping ratios. Measurements on an electrodynamic shaker will be performed using synthetic shock-time histories for different shock durations. Using the dynamic properties and shock-time histories obtained from shaker measurements, simulations of single-mass oscillators will be carried out using MATLAB for the solution of the ordinary differential equation of motion. Simulations on the real geometry of the oscillator will be finally performed using the FEM software ABAQUS. The results will be compared and conclusions and recommendations will be given for the simulation of high-voltage batteries.

## 2. EXPERIMENTS

### 2.1 Experimental setup

The relevant eigenfrequencies of high-voltage batteries are typically in the range from 10 Hz to 300 Hz (Dörnhöfer, 2018). In order to represent the battery vibration behavior, a specimen with eigenfrequencies in the same range is designed. The specimen consists of four separate test strips with same thickness but different lengths and is made from steel. The dimensions of the test specimen are shown in Fig. 2.

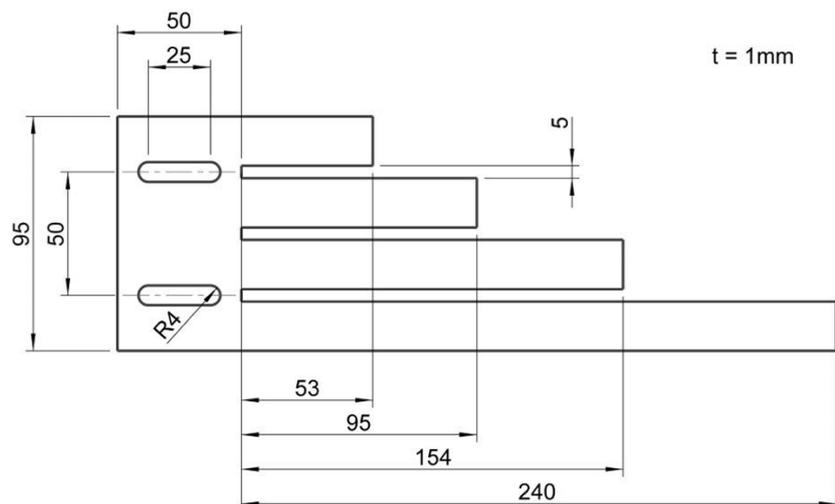


Figure 2. Dimensions of the specimen for shock measurements (all dimensions are given in mm)

To apply the shock loads to the specimen, it is attached to an electrodynamic shaker. The shaker has its own controller and follows the test programs specified later. The shock response of the specimen is obtained by a direct comparison between the base acceleration and the shock responses of the individual test strips. For this purpose, acceleration sensors are applied to the ends of the test strips as shown in Fig. 3. Due to their low weight, the influence of the sensors on the vibration behavior of the specimen is marginal.

For the determination of the eigenfrequencies of the individual test strips, the specimen will be excited using a sine sweep which is a signal with increasing frequency and same acceleration amplitude. The eigenfrequencies are then determined using Fast Fourier Transformation (FFT). Only frequencies in the range between 0 and 300 Hz will be taken into account. Table 1 shows the eigenfrequencies of the test fingers determined by FFT.

To determine the damping, the individual strips are deflected and then released to produce a damped natural oscillation in the first eigenfrequency. The damping can be determined from the measured acceleration responses using the method of logarithmic decrement analyzing the decay behavior of the oscillation. The measured damping values are given in Table 2, represented by the damping ratio  $\theta$ . As can be seen, the damping values differ depending on the strip and are in general lower than 1%. The damping values obtained here will be used for the simulation with MATLAB and ABAQUS later.

Based on the eigenfrequencies given in Tab. 1, a test program shown in Tab. 3 has been created. The different shock durations are obtained by building the reciprocal value from the eigenfrequency and further dividing it by two. The idea



Figure 3. Acceleration sensors on the test strips

Table 1. Eigenfrequencies of the test strips No. 1-4, determined in experiments

Test strip 1 [f in Hz]	Test strip 2 [f in Hz]	Test strip 3 [f in Hz]	Test strip 4 [f in Hz]
14	32	80	232
84	204	-	-
232	-	-	-

Table 2. Damping ratios of the test strips No. 1-4, determined in experiments

Test strip 1 [ $\theta$ in %]	Test strip 2 [ $\theta$ in %]	Test strip 3 [ $\theta$ in %]	Test strip 4 [ $\theta$ in %]
0.43	0.32	0.62	0.72

behind this procedure is the simplified assumption that the individual test strips will be excited most by a half-sine signal with the same period of oscillation as the eigenfrequency. It is assumed that test strips with lower eigenfrequency will get more into resonance using a signal with longer shock duration and vice versa. The chosen shock level represents loads which occur in real service situations. All tests are carried out at room temperature.

Table 3. Test program for shock measurements

Shock level [g]	Shock duration [ms]	Shock form
3	2; 6.3; 15.6	Half-sine

## 2.2 Experimental evaluation

For the evaluation of the shock response, it is necessary to take a closer look on the base excitation first. Due to the shaker control strategy, there is always a pre- and a post-shock occurring before and after the actual half-sine signal, see Fig. 4. The form and the amplitude of the pre- and post-shock vary depending on the shock duration. Usually, longer

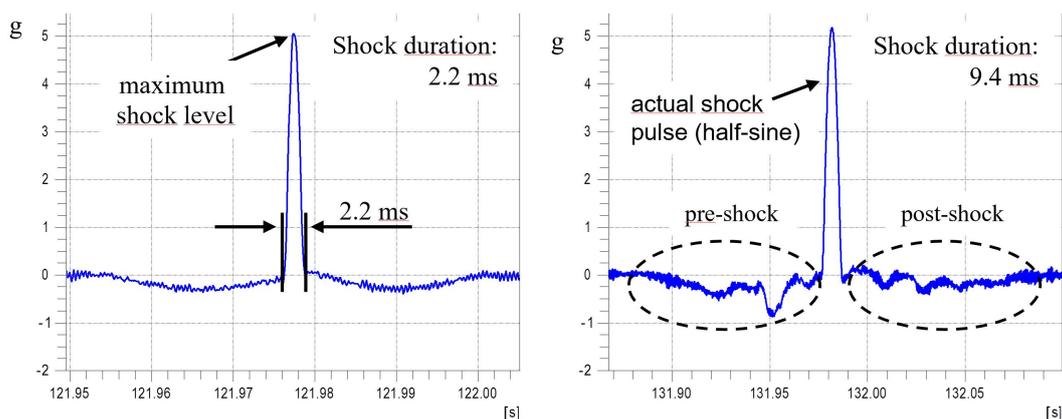


Figure 4. Shock excitation analysis for different shock durations

shock durations result in higher irregularity of the shock signal as applied by the shaker. It is important to take the real time history of the shock signal into account when simulating batteries as the signal irregularity can induce additional excitation of the components. Therefore, measured excitation histories will be used for the numerical simulation as discussed in the next chapter.

For the comparison with simulation results, the maximum response acceleration will be evaluated like shown in Fig. 5.

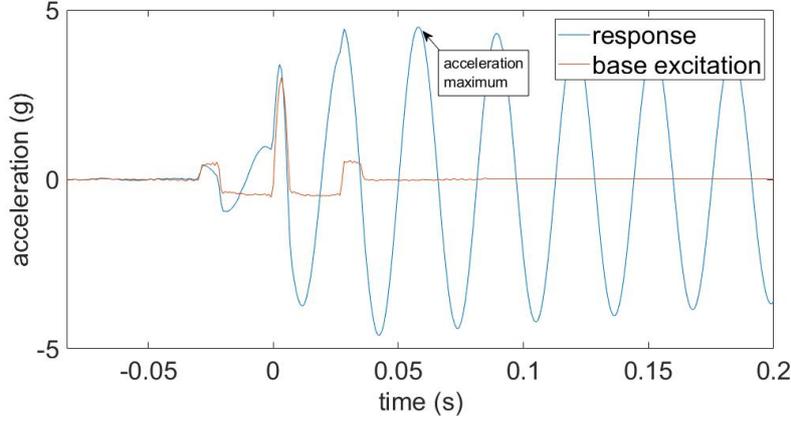


Figure 5. Shock response analysis

### 3. NUMERICAL SIMULATION

#### 3.1 Simulation of single-mass oscillator using MATLAB

The vibration behavior of the test strips will be calculated on the basis of an single-mass oscillator like shown in Fig. 6 using MATLAB.

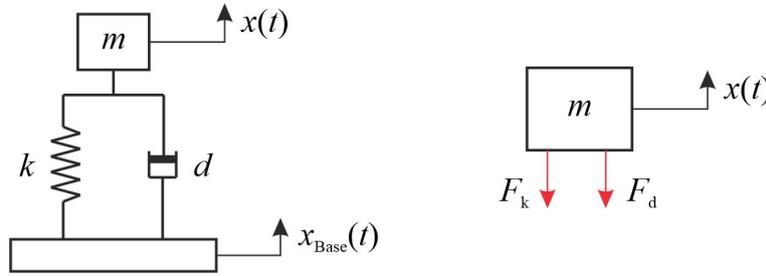


Figure 6. Single mass oscillator model

The force equilibrium for the mass  $m$  using the inertial force, the spring force  $F_k$  and the damping force  $F_d$  and introducing the relative movement  $x_{rel} = x - x_{Base}$  delivers:

$$m\ddot{x} = -d\dot{x}_{rel} - kx_{rel} \quad (1)$$

Reshaping the equation  $x_{rel} = x - x_{Base}$  into  $x = x_{Base} + x_{rel}$  and  $\ddot{x} = \ddot{x}_{Base} + \ddot{x}_{rel}$ , respectively, Eq. (1) can be stated as:

$$m\ddot{x}_{rel} + d\dot{x}_{rel} + kx_{rel} = -m\ddot{x}_{Base} \quad (2)$$

Equation (2) can now be reshaped to obtain the relative acceleration of the mass  $m$ :

$$\ddot{x}_{rel} = -\frac{d}{m}\dot{x}_{rel} - \frac{k}{m}x_{rel} - \ddot{x}_{Base} \quad (3)$$

Using Eq. (3), the mass movement will be calculated numerically for given eigenfrequency, damping ratio and shock signal using the MATLAB solver ODE23s for ordinary differential equations.

### 3.2 FE simulation

For the simulation in ABAQUS, an FE model has been created, see Fig. 7. The model consists of linear shell elements S3R and S4R with reduced integration. The masses of the acceleration sensors have been considered using mass elements. Material properties of steel with the Young's modulus  $E = 210.000$  MPa, Poisson's ratio  $\nu = 0.3$  and density  $\rho = 7.85$  g/cm<sup>3</sup> have been used. As previously mentioned, the measured damping ratios and shock histories are used for the FE simulation. An implicit transient dynamic simulation using the base acceleration history is performed and the maximum acceleration is determined from the transient response of the individual test strip.



Figure 7. FE model of the test strips

## 4. RESULTS AND DISCUSSION

The results from experiment and simulation are presented in Fig. 8. It can be observed from all methods that the different test strips have a different response depending on the shock duration. Test strips with higher eigenfrequency show a higher acceleration when using a signal with shorter shock duration; the same applies vice versa.

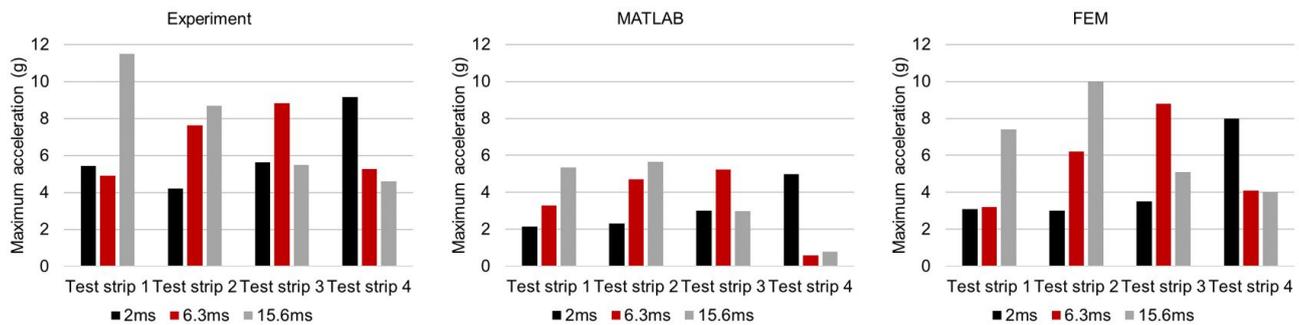


Figure 8. Comparison of experimental and numerical results for the response accelerations using different shock durations (half-sine, 3g, evaluation of shock maximum)

It can be seen from Fig. 8 that the largest accelerations occur in experiment. In contrast, the lowest accelerations are delivered by the MATLAB simulation. An important reason for the deviations in MATLAB simulation is the fact that in this case only the first eigenfrequency of the test strip is taken into account. Since shock pulses produce a broadband vibration (Lalanne, 2009), also the higher eigenfrequencies will be excited in addition to the first eigenfrequency in real components. The superposition of different eigenfrequencies can finally lead to higher accelerations during the excitation. It can also be observed that the FEM results deliver similar absolute values compared to experiment.

In the next step, the absolute values will be normalized for each test strip in order to obtain a relative comparison between the methods. The normalized results are shown in Fig. 9. It can be seen that comparing the normalized values all methods deliver very similar results. This is the case especially for the test strips 1-3. In case of test strip 4 larger deviations occur. A possible reason for the deviation could be the fact that the shock signal delivered from the electrodynamic shaker is superimposed by vibrations with higher frequency, see Fig. 4, which could excite vibrations with higher frequency.

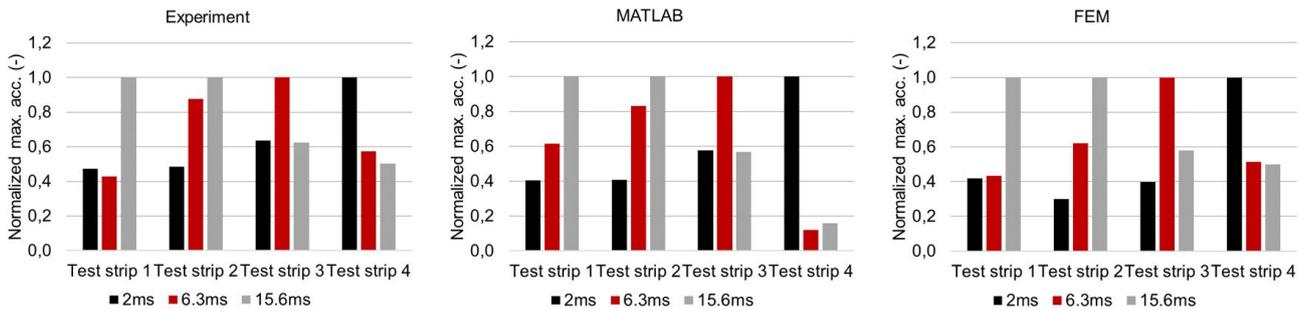


Figure 9. Comparison of experimental and numerical results for the response accelerations using different shock durations (half-sine, 3g, evaluation of shock maximum), normalized for each test strip

## 5. SUMMARY

This paper presents methods for simulating shock loads for high-voltage batteries and investigations are carried out concerning their accuracy. A single-mass oscillator simulation and an FEM simulation are developed and compared with dynamic measurements using a test body. Taking into account the results from experiment and simulation it can be concluded that the FEM method is most suited for the calculation of absolute values. Especially for the part design, when local stresses must be calculated, the use of FEM simulation is essential. The MATLAB model only considers a single-mass oscillator. At the same time, the superposition of several eigenfrequencies is not taken into account, which results in values significantly below the actual values, especially when determining the absolute values. Nevertheless, when only different shock signals are compared with respect to their damage content, the use of single-mass oscillators is a very fast and effective method.

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