STOCHASTIC MODELLING OF THE ES-2 DUMMY FOR ROBUST DESIGN

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ABSTRACT
Physical crash test dummies of one type, such as the ES-2 side impact dummy, are not perfectly reproducible due to production and certification tolerances. This means that similar crash tests with various ES2 dummies will have varying results, called experimental scatter. New car designs should be insensitive to this scatter, thus the design is robust. As robustness analyses are very cost effective using numerical simulations, there is a need for a numerical dummy model, which incorporates the experimental scatter data. Such model is called a stochastic dummy model. Therefore, the existing MADYMO ES-2 model was modified to represent a wide range of experimental data, thus creating a stochastic ES2 model. An example of a side impact application shows the use of the stochastic ES-2 model to evaluate design robustness.

Keywords: Component tests, ES-2 dummy, multibody, optimization methods, stochastic analysis

CAR CRASH SIMULATIONS, INCLUDING VIRTUAL DUMMY MODELS, play an important role in the design process of restraint systems. These virtual models are based on physical dummies. However, real life crash test dummies of one type are not perfectly reproducible due to fabrication and certification tolerances. Certification tests are used to ensure that dummy responses are not out of range. Unfortunately, since dummies are certified within some tolerances, dummies may vary among each other significantly. We refer to these variations as stochastic parameters. The virtual dummies should exhibit similar stochastic parameters as their physical counterparts to support the design of restraint systems, which are insensitive to the stochastic parameters. The design is then called robust.

This paper aims at the development of a stochastic version of the ES-2 dummy. The ES-2 dummy is used for side impact regulatory crash tests (FTSS, 2002). Starting point for the stochastic ES-2 dummy model is the deterministic ES-2 dummy model released with MADYMO release 6.3. This dummy model is built from multibody elements and uses facet surfaces for the geometric representation of the dummy. The compliance of the soft dummy materials is represented with contact characteristics defined for the representing facet surfaces.

In the work of Dalenoort et al. (2005), a stochastic model of the Hybrid-III frontal dummy model has been developed. They defined stochastic parameters based on the corridors of experimental certification tests. However, the stochastic parameters are not based on the physics of individual certification tests. In this study, the values of the parameters are determined by modifying the deterministic model using optimization methods based on each experimental certification test separately. By combining the varying parameters of all certification tests, distributions of the stochastic parameters are determined.

STOCHASTIC MODELLING
The ES-2 dummy consists of several components that have to be certified: head, neck, rib module, and lumbar spine. For details on the certification tests of each of these components is referred to the ES-2 user’s manual (FTSS, 2002). The experimental data of these component tests are selected for 50 individual dummies. For each component 50 valid certification tests are selected representing an equal number of individual components. Since each dummy consists of three rib units, 17 dummies are selected which results in 51 individual rib unit component tests. Since individual component tests are used, the stochastic parameters of the stochastic model apply to the differences among the components, e.g. caused by production variation.

For each component the most sensitive and physically related parameters regarding the responses
of the certification tests are selected as tuning parameters. All parameters are related to contact characteristics and joint stiffness entities, since these parameters represent physical behaviour of multibody components. With 50 experimental certification data sets available, the deterministic model can be tuned with respect to the tuning parameters. An optimization algorithm is used to correlate the experimental responses to the simulated responses. Since the parameters are tuned for each individual certification test, this results in a set of values for each stochastic parameter. It is assumed that the values of the stochastic parameters are distributed according to a Normal distribution. In the end, the stochastic model has to be validated using Monte-Carlo simulations of the certification tests. The next two sections describe (1) the optimization of the tuning parameters and (2) the validation, respectively.

OPTIMIZATION

The responses are tuned using an optimization algorithm. The optimization algorithm lsqnonlin in Matlab, which minimizes the sum of squared errors (SSE), is used for this purpose. Responses are mainly tuned with scaling parameters of loading and unloading functions. For the neck and lumbar spine certification tests, the pendulum acceleration and velocity information is taken into account. Assuming a scale parameter, the following tuning parameters have been selected:

- **Head**: The acceleration response of the head drop test is sensitive to the contact properties of the vinyl skin. The contact properties are described by the contact loading, unloading, and damping-velocity (DV) function. The scale parameters are referred to as VinylLoaX, VinylUnlX, and VinylDVY, respectively.
- **Neck**: The angular responses of the neck pendulum test are sensitive to the stiffness of the upper and lower neck joints (neck buffers) and the rubber mould. Parameters InterfaceBendingX and InterfaceBendingDVY represent the stiffness and damping-velocity scale parameters of the upper and lower neck joint characteristics. Parameters MouldBendingX and MouldBendingDVY represent the stiffness and damping-velocity scale parameters of the rubber mould.
- **Rib unit**: The deflection response of the rib unit certification test is sensitive to the contact properties of the flesh simulating foam and the stiffness of the steel rib bow. The foam contact characteristics are described by a combination of a loading, unloading and a damping velocity function. Parameter FoamX and FoamY represent the x-scale and y-scale stochastic parameter of the contact loading and unloading functions. Parameter SteelY represents the y-scale parameter of the loading and unloading function of the stiffness of the steel rib bow.
- **Lumbar spine**: The angular response of the lumbar spine certification test is sensitive to the stiffness of the rubber mould and steel cable. Since the stiffness parameters of both elements have an equal effect on the response, only the spine mould stiffness is assumed to be stochastic. Parameter MouldBendingX represents the x-scale parameter of the stiffness of the spine mould for loading and unloading.

The values of the tuned stochastic parameters are summarized in Table 1. This table shows the mean value of the scale parameters, which are normalised to 1.0 (due to confidentiality reasons). Furthermore, the standard deviation (std), the minimum (min) and maximum (max) value are given.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Direction</th>
<th>Mean</th>
<th>Std</th>
<th>Min</th>
<th>Max</th>
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<td>Head</td>
<td>VinylLoaX</td>
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<td>0.895</td>
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<td>VinylUnlX</td>
<td>x-scale</td>
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<td>0.069</td>
<td>0.912</td>
<td>1.331</td>
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<td>VinylDVY</td>
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<td>0.173</td>
<td>0.542</td>
<td>1.326</td>
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<td>Neck</td>
<td>InterfaceBendingX</td>
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<td>0.034</td>
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<td>1.090</td>
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<td>InterfaceBendingDVY</td>
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<td>0.472</td>
<td>1.817</td>
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<td>0.049</td>
<td>0.884</td>
<td>1.134</td>
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<td>Rib unit</td>
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<td>0.078</td>
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<tr>
<td></td>
<td>SteelY</td>
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<td>0.860</td>
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<tr>
<td>Lumbar Spine</td>
<td>MouldBendingX</td>
<td>x-scale</td>
<td>1.000</td>
<td>0.048</td>
<td>0.930</td>
<td>1.135</td>
</tr>
</tbody>
</table>
VALIDATION

With the distribution of the stochastic parameters available, a stochastic analysis can be performed. The parameters are assumed to be normally distributed, according to the mean and standard deviation of Table 1. For each component 50 stochastic simulations of the certification tests are performed based on Monte-Carlo sampling. The results of these 50 validation simulations are compared to the experimental data with respect to the mean and standard deviation of the peak responses. The validation results are given in Figure 1 showing the original experimental data in grey and the 50 Monte-Carlo simulations as black dotted curves.

- **Head**: All the simulations are valid according the certification requirements. During the loading phase the simulations follow the bounds of the experimental data. During the unloading phase the simulations are slightly overestimating the acceleration. The mean value and standard deviation of the peak value of the acceleration are closely estimated.

- **Neck**: During the loading and unloading phase the simulations follow the bounds of the experimental data. All simulations are valid according the certification requirements based on the timing of the peak angles. One simulation out of fifty did not certify based only on the peak angle. The mean values of the peak value of the angular response are closely estimated by the simulations. The standard deviation is slightly underestimated.

- **Rib unit**: All the simulations are valid according the certification requirements. During the loading and unloading phase the simulations follow the bounds of the experimental data. The mean value and standard deviation of the peak deflection are closely approximated by the simulation experiments. Only at the final stage of the certification test (after 60 ms), the simulations do not follow the experimental curves anymore. At this stage the end stop of the rib unit is reached after returning to zero deflection, resulting in somewhat noisy behaviour.

- **Lumbar spine**: The mean peak value of the angular response of the angular response is closely estimated by the simulation experiments. The standard deviation is slightly underestimated. The simulations do not completely follow the bounds of the experimental data during the loading and unloading phase of the angular bending. Based on the certification requirements, the peak values are valid. The simulations do not certify based on the timing of the peak.

![Validation of the certification simulations](image)

**Fig. 1 – Validation of the certification simulations**
APPLICATION

As a showcase, a generic vehicle side impact compartment model has been adopted. The model represents a EuroNCAP barrier side impact with the stochastic ES-2 dummy model (see Figure 2(a)). The door has a prescribed structural motion on the inner door panel and includes an FE foam block and an FE door trim. The motion of the B-pillar and the seat are also prescribed. An FE thorax airbag is added. Although the model is not validated against test data, realistic dummy kinematics and response signals are obtained.

The injury parameter scatter that could be expected in EuroNCAP side impact tests, involving a vehicle similar as in the showcase model, will be calculated using the above described model in ModeFRONTIER. Input for this analysis is scatter information of the stochastic parameters of the ES-2 dummy (see Table 1). An experimental setup of 150 simulations is built up with Monte-Carlo sampling. Figure 2(b) shows a histogram of the injury criteria highlighting the injury scatter extracted from the 150 simulations due to scatter input parameters of the ES-2 dummy.

CONCLUSIONS

Stochastic dummy models are needed in virtual crash test methods to account for the differences among dummies. A stochastic model of the ES-2 dummy was developed successfully. This stochastic model can be used in robust design of, e.g., restraint systems. Currently used robust design methods require a vast number of simulations. This paper shows that using the stochastic ES-2 dummy model, which is computationally fast, robust design methods can be used efficiently to improve crash safety.

The use of optimization algorithms leads to high quality dummy responses. With the selected tuning parameters, the simulation models of all four certification tests were able to capture the physics of each of the experimental certification curves. Only for the lumbar spine model some physics to describe the bending responses in the loading and unloading phase are missing. It is assumed that stochastic influence of the certification tests itself can be neglected. For the pendulum tests of lumbar spine and neck, scatter introduced by the test setup is included in the stochastic parameter tuning, since the acceleration and velocity information of the pendulum is used.

The full dummy certification tests for abdomen, pelvis, and shoulder are not included in this study. These certification tests can be used to include also stochastic parameters for the full dummy.

References


FTSS, ES-2 Eurosid-2 50\textsuperscript{th} percentile side impact crash test dummy, User manual, Guidelines for test-engineers and dummy technicians, February 2002.