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Importance of uncertainties in non-linear simulation and testing for engineering design

Laszlo Farkas[1], Stijn Donders[1], Gianpiero Rocca[1], Bart Peeters[1], Herman Van der Auweraer[1], David Moens[2]
[1]LMS International, Interleuvenlaan 68, B-3001, Leuven, Belgium
[2] Lessius Hogeschool, Department of Applied Engineering, K.U.Leuven Association,
J. De Nayerlaan 5, B-2860, Sint Katelijne Waver, Belgium
email: laszlo.farkas@lmsintl.com

ABSTRACT: Nowadays, mechanical industries operate in a highly competitive environment, therefore the process of developing a component from concept through detailed CAE and performance validation is optimized for reduced development time and increased product performance. In order to continuously improve the product design and performance, and reduce the costs and time to market, the design and performance engineering is shifted more and more towards virtual modelling and simulation processes from the expensive test-based design evaluations. A second evolution is the booming introduction of active and adaptive systems in mechanical structures, leading to a 'mechatronics systems' revolution to further push the product performance to higher levels, however at the expense of increased system complexity. Here, it is noted that the potential of structural dynamics test and analysis methods for addressing a structural dynamics design assessment or design optimization, depends largely on the confidence that one can have in the results. In this context, a key aspect is to be aware of the key sources of uncertainty in the designed product, and the impact thereof on the product performance. The product nowadays can often no longer be seen as a linear mechanical system, but rather as mechatronics systems and/or as a mechanical system with distinct nonlinear behaviour for certain performance criteria of interest. This paper reviews the main elements of test data and modal modelling uncertainty and assesses the impact of the uncertainty on some typical modelling problems. Some recent methods for uncertainty analysis in modelling are addressed. Examples include a vehicle bumper system analyzed for crashworthiness, the mechatronics system design challenge and structural analysis of vehicle and aeronautics structures.
KEYWORDS: uncertainties, non-linearity, crash, mechatronics systems

1 INTRODUCTION

In real-life structures, not all parameters are exactly defined. Non-determinism in input parameters results in scatter on the output properties that is not taken into account by a deterministic optimization. Therefore, fine tuning the deterministic input parameter settings without taking into account the real-life scatter on these parameters may result in a design for which the stability targets on the outputs are violated. When performing deterministic optimization, it should be taken into account that realistic uncertainty and variability on the inputs may propagate into scatter on the outputs. This, in turn, may lead to a violation of the constraints on performance targets. For this purpose, the robustness and reliability attained at the deterministic optimum should be assessed:

- Robustness is related to the sensitivity of the cost function to small changes in the inputs. A robust design is insensitive to the scatter in the input parameters.
- Reliability refers to the probability that a failure is attained as a result of input variability. A reliable design has a low failure probability with respect to pre-defined failure constraints.

Although the non-deterministic nature of the functional performance of mechanical structures is generally agreed upon, non-deterministic modelling and simulation have not yet become a mainstream activity in vehicle development processes at OEMs and suppliers. The ever continuing advances in terms of IT resources are mainly being dedicated by analysts to increasing CAE model complexity, for which then only a limited number of deterministic simulations are performed. This can be explained based on two key gaps in the state-of-the-art and state-of-the-use:

- Robust and reliability-based design optimization cycles typically require hundreds of deterministic analysis runs, so that choosing for this approach involves huge computational effort or a reduction of model fidelity (and consequently computational time).
- Quantification of (non-)deterministic data is a key challenge to include representative models of non-determinism in the design engineering process. Typically, insufficient (distribution) data is available, and the cost to collect enough data is too high (e.g. repetitive experimental studies on dedicated components and samples).

A traditional approach of taking into account the impact of design uncertainty is to include safety factors in the design, which however leads to sub-optimal designs with excessive weight and/or material usage. Better results can be achieved by introducing the uncertainty in the design process, and by taking account its impact in the design process.

This paper reviews the main elements of test data and modal modelling uncertainty and assesses the impact of the uncertainty on some typical modelling problems. This includes a vehicle bumper subsystem analyzed for crashworthiness, the mechatronics system design challenge and structural analysis of vehicle and aeronautics structures.

SOURCES OF UNCERTAINTIES IN DIFFERENT DESIGN ENGINEERING DISCIPLINES

1.1 Automotive crash and safety simulations

The vehicle crash event is a dependent sequence of bifurcation driven responses of parts coming into contacts, involving ruptures (failures of parts, connections), each sub-system response being highly dynamic and non-linear ([1], [2]). This highly transient dynamic non-deterministic event shows high sensitivity with respect to uncertainties. Therefore key uncertainties must be accounted for already in the virtual design phase. This becomes crucial in the context of an optimization process for robustness and reliability. In the automotive design for crashworthiness there still exist several modelling challenges concerning material behaviour, modelling of connections (e.g. spot-welds). Such difficulties arise in finding accurate failure models, accurate capturing of strain-rate and temperature dependent material behaviour, and modelling of plastics and foam materials, which leads to model non-determinism.

It is noted in [3] and [4] that in safety simulations implying virtual crash-test-dummies, several factors need special attention for a realistic dummy response. These factors are dummy positioning, correct restraint-systems and sub-assemblies interaction capturing, foam and other key material modelling. These factors carry some degree of uncertainty, which together with the inherent and uncontrollable numerical noise make the safety simulations non-deterministic. As a natural consequence the virtual certification tests imply the usage of compliance corridors and acceptance windows. Moreover, the validation process becomes more demanding and time-consuming in both the crash and the safety simulations.

Another non-deterministic factor that influences the robustness of the results is introduced by the numerical scatter. Widely used crash predictor algorithms based on the explicit time integration scheme have to deal with approximation errors. The repetitive time-step integration sums up these errors (and the round-off errors) into the numerical noise which has to be small in comparison to the scatter due to model-parametric uncertainties. Non-linear contact problems with multiple bifurcations in combination with numerical noise result in large response variation without significant physical parameter variation. Numerical scatter is influenced by the choice of contact models, failure models, strain-rate effect in non-linear material model, element formulation, damping, mesh quality. This aspect, together with the natural existence of semi-controllable (at increased cost) and controllable model-parametric uncertainties such as dimensional tolerances, material parameters, positioning and initial conditions emphasizes the need of uncertainty assessment in automotive crash and safety simulations.

Section 2.1 presents a study of a vehicle bumper subsystem subject to model uncertainties and their effect on the crash performance. Furthermore, the added value of the uncertainty-based design optimization will be illustrated in the optimization study of the bumper subsystem.

1.2 Mechatronics system design

One of the major evolutions that is currently taking place in mechanical industry is the increase of the electronic and mechatronic content in order to push the performance upward, and hence the product value and reliability. This is the case for the automotive as well as aerospace/aeronautics sectors. As a result, the industry is facing no longer the mere challenge to design and develop a mechanical structure, but has to deliver mechatronics structures to the market, and adopt its design, development and validation procedures to the changing needs of their final products. In terms of reliability engineering, the mechatronics evolution has a dual impact:

- on the one hand, there’s a drastic increase in the system complexity, with additional sources of model uncertainty and subsystem failure possibilities. This calls for a systematic analysis of the mechatronics system model, a sensitivity analysis on possible sources of uncertainty, and the development of systematic failure mode and effect analysis methods to understand the chain of events from subsystem failure up to system-level performance failure.
- on the other hand, the introduction of controls systems allows new strategies to mitigate the effect of model uncertainty and subsystem failure by means of control strategies to compensate for a given uncertainty or to switch to an alternative mode of operation that maintains the system performance at an acceptable level.

The booming introduction of active and adaptive subsystems is irreversible, in that it allows industry to push higher the product performance bar by optimizing not merely the mechanical performance but instead the mechatronics system performance of the products. For instance in vehicle industry, active systems (ABS, ESP, active suspension, active steering...) are key to increasing the vehicle comfort and safety of new products that are brought to the market [5]. However, automotive manufacturers must ensure the reliability of the mechatronics systems, since each failure that occurs will be put under a magnifying glass in terms of media attention. This has been seen in recent years in the media, with reports on mechanical failures in new electronics components, causing vehicles to turn inactive now and then. This potential negative ‘branding’ in case of failures pushes the bar very high for industry in its quest to guarantee the system reliability of its mechatronics products.

Uncertainties in mechatronics systems can be distinguished on several levels:

- sensor level
- actuator level
- data acquisition and post-processing level
- cascading from subsystem to system level

Uncertainties that are present on the level of sensors and actuators introduce errors that need to be accommodated by the control, or for which robustness must be built into the system design ([6], [7], [8]). This can be deviations from the nominal linear parameters such as sensitivities and gain or phase factors in all sorts of components and subsystems (material parameters, electric gains, filter cut-off frequencies…), but also very important is that most of these mechatronic interface components are to some degree

nonlinear. This is in particular the case for the actuator systems [9]. Even when this nonlinearity is seemingly included in the applied models, this is typically a functional approximation that leaves part of the actual nonlinear behaviour unmodelled. The propagation to the actual system level behaviour may even be that the controller, designed based on the linear or simplified system model, becomes unstable. Hence the validation of the robustness of the control functional behaviour under deviations of the actual system model with respect to the design model is very important [10].
Further complexities in the mechatronics systems approach may be related to the fact that inputs needed by the control system are not readily available from direct measurement. This leads to need for a state-estimation procedure (and subsystem in the controller), which will be typically designed for uncertain system parameters as well as for measurement noise [8]. For example, measurement noise on a displacement signal which needs to be differentiated to a velocity signal may be significantly subject to amplification. Unmodelled nonlinear system behaviour may distort the state estimator as well. Kalman filters may be adopted to balance the effect of measurement and the modelling errors. But also intrinsic uncertainties may influence the state estimation process, for example the unknown weight and inertia distribution in a car due to driver, passenger and luggage. Insufficient measurement data is typically available to correctly identify these properties and to use them in a state estimation procedure, hence the use of optimization processes and the need for robust control methods.
Naturally, also mechanical uncertainty remains an important aspect for understanding the uncertainty of mechatronics systems. This comprises uncertainty in material properties of subsystems, connectivity between subsystems, modal mass and damping properties on a (sub)system level, … . The latter aspect will be covered in Section 1.3. In Section 2, two uncertainty assessment examples in mechatronics systems will be presented, covering a virtual shaker testing campaign of a satellite and a non-linear uncertainty study case of a vehicle suspension system.

1.3 Modal analysis

Experimental Modal Analysis has evolved to a widely accepted methodology in the analysis and optimisation of the dynamic behaviour of mechanical and civil structures. Modal tests are a standard part of the analysis and refinement of physical prototypes or even operational structures. The modal model results are considered to be a deterministic system description, which can be used for multiple applications, ranging from a mere verification of the fulfilment of the design criteria, to the validation and updating of CAE models and the integration in hybrid system models.
In reality, the modal results are just an estimation of the model parameters based on a series of input-output or output-only tests and hence subject to all related testing and modelling errors. These data errors can be just stochastic disturbances on the input/output data, but can also be caused by invalid model assumptions or data processing effects. Some of the main sources of errors are:

- Sensor location and orientation errors
- Test set-up loading and constraining effects
- Sensor loading effects on the test structure
- Sensor calibration and data conversion errors
- Disturbance and distortion in the test data measurement chain
- Signal processing errors
- Model estimation errors

These error sources as well as the commonly used approaches to reduce these are briefly reviewed in [6]. More extensive discussions can for example be found in [11]. Since all modal tests are to a larger or lesser degree subject to such errors, the modal parameters can only be known up to a certain degree of uncertainty.
Section 2.3 presents an example of uncertainty in a vehicle system identification process. The uncertainties in the identified system parameters are caused by the non-linear system behaviour. These nonlinearities caused by vehicle system components such as bushings or tyre are not well captured in the commonly used system identification methods. A comparison of two different modal analysis methods is discussed in the context of vehicle suspension monitoring.

2 APPLICATION EXAMPLES

2.1 Fuzzy optimization study of a vehicle bumper subsystem subject to uncertainties

Bumper systems play an important role in the energy management of vehicles during low-speed accidents. Optimisation technology and automation enables efficient balancing between different performance attributes. Optimisation is typically done without considering the different model uncertainties such as properties subject to tolerances, environmental effects, non-uniform material properties, etc. The possibility-based design optimisation (PBDO) process that implies fuzzy finite element (FE) analysis allows the designer to include the effect of non-deterministic model properties in the design performance optimisation of the bumper subsystem [12]. The bumper subsystem optimisation based on this rationale results in product performance that is guaranteed in the presence of uncertainties already from the early design stages.

An industrially representative FE bumper assembly has been selected (see Figure 1) to demonstrate the use and the added value of the PBDO methodology in the design optimisation process. The bumper is subject to two different crash load cases (Allianz reparability test AZT and the pole-impact test) and 5 different uncertain design parameters (3 geometrical dimensions and 2 shell thicknesses, representing production tolerances).

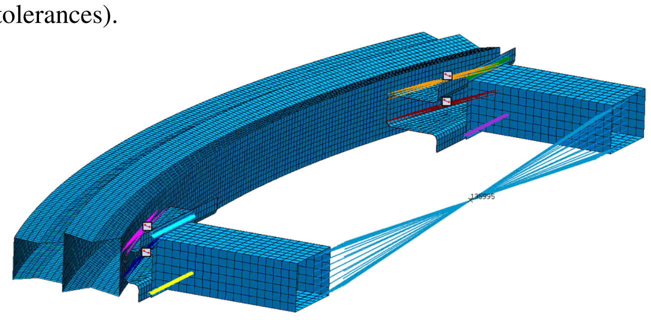

Figure 1: FE mesh and assembly of the bumper system

The effect of the range of the uncertain bumper parameters is evaluated for the Allianz crash load case. The uncertainty effect on cross longitudinal beam sectional normal force is shown in Figure 2. The curve indicates the energy absorption capability of the bumper: the area under the curve is the equivalent to the initial kinetic energy that is transformed into deformation energy. Important design constraint for this particular load case limits the largest normal sectional force which is correlated to the deformation length.

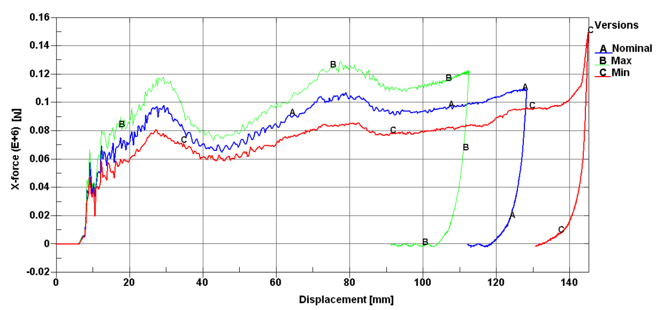

Figure 2: effect of uncertain parameter range on AZT force-displacement curve

The largest deformation length is a characteristic of the geometry of the bumper design equal to approximately 140mm. The red curve indicates that the design based on the lowest parameter values has already reached the full energy absorption potential. This is clearly indicated by the peak in the normal sectional force reaching over 14kN value after the full collapse of the bumper section. It can be concluded that the typical manufacturing tolerances have large influence on the design response, which need to be considered for robust and optimal design.

The bumper is optimised for weight (quantified by the variable “Mass”) and AZT force-displacement curve profile (quantified by the variable “RMSE Fx,” while applying a constraint for each load case. The central intrusion (quantified by the variable “Max Int”) is limited for the pole-impact load case and the largest cross sectional normal force (quantified by the variable “Max Fx”) is limited for the AZT load case. Two optimisation strategies are compared:

- Classical crisp optimisation, which is followed by the uncertainty assessment of the optimum
- Optimisation process that takes the effect of parametric uncertainties into account, such that the system level of failure possibility is acceptable. The possibility of failure is function of the degree of constraint violation

Figure 3 compares the results of two optimisation scenarios. The first scenario is based on a classical crisp optimisation is compared with the second optimisation scenario considering model uncertainties. The uncertainties modelled with triangular membership functions based on the concept of fuzzy numbers are propagated by the means of the fuzzy FE method ([13], [14], [15]). It is important to notice that the crisp optimum converges to a design point which violates the constraint applied on the AZT load case.

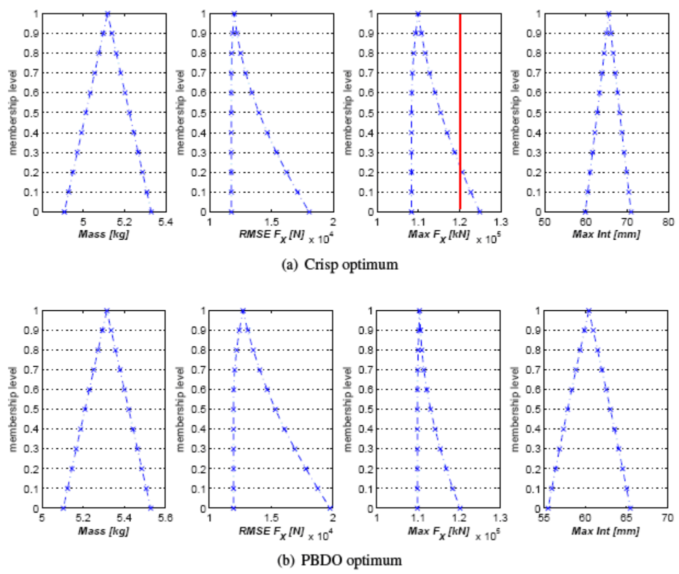

Figure 3: The fuzzy optimums for the two different optimization cases

This comparison demonstrates that the PBDO-based optimization approach leads to an optimized design performance that is guaranteed in the presence of uncertainties.

2.2 *Controller design for virtual shaker*

In this section, the fuzzy uncertainty modelling technique (based on the Transformation Method [16]) is applied in the field of controls engineering, for the assessment of the controller robustness in a virtual shaker test of a satellite. Virtual shaker testing of a satellite is important to ensure safe launch conditions. A virtual shaker testing approach has been developed [17], consisting of a coupled electro-mechanical model and a vibration controller. The shaker table and controller must be designed such that critical launch conditions can be tested without damaging the satellite. Moreover, the controller performance must be guaranteed for the realistic range of satellite model uncertainty (e.g. in modal damping parameters).

A parameterized simulation model of the satellite in controlled virtual shaker conditions has been created, comprising a dynamic multi-body simulation (MBS) model of the satellite and a controller model in Simulink [10]. The sine controller has been coupled to the satellite model, with the controller output directly applied as a force input to the structure (i.e. assuming a perfect shaker). A parameter sensitivity study has been performed [18] to assess the influence of uncertain satellite model parameters on the control quality. While mass and stiffness properties are relatively well known in general, understanding the nature and being able to quantify damping mechanisms in structures is a much more difficult task. Therefore, it is important to take large uncertainties into account when modelling damping. As a case study, the two main satellite modes (i.e. the ones having the largest effective mass: the modes at 37Hz and 42 Hz, respectively) have been selected as uncertain parameters. The spring and mass properties are kept constant, but a large variation of the damping ratio is considered: = 0.5 – 10 %.

The sine control test specification comes typically in the form of an acceleration spectrum that needs to be reproduced at the shaker table. In this case, the profile was linearly ramping up (on a log-log scale) between 1 and 10 Hz and then kept constant till 100 Hz. See the nominal spectrum in Figure 4.

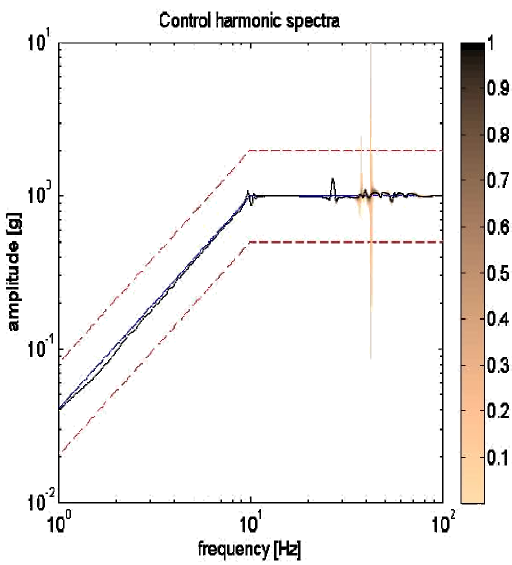

Figure 4: Uncertainty plot with nominal control parameters.

After modelling the uncertainty in the modal damping characteristics, the Reduced Transformation Method is used to assess the effect of uncertainties on the controller performance, for the design range of controller settings. Two controller parameters, the compression factor and the number of periods in the sine sweep, can be varied by the engineer to optimize the controller performance. It is of high interest to be able to determine for which controller parameters the impact of the (given) satellite uncertainty is minimal. A systematic uncertainty assessment has been performed for this purpose. A three-level full factorial Design of Experiments (DOE) has been performed on the two most important controller parameters (see definitions below). This allows presenting the fuzzy uncertainty on the controller response in a 3x3 display of fuzzy controller performances (see Figure 5), from which both the worst-case scenarios and the best choice in controller settings can easily be identified.

- Left to right, the compression factor (*c*), which determines the control agility, increases. A low factor means more agile control at the expense of "noisier" spectra and increased likelihood of beating.
- Bottom to top, the number of sine periods *(p)* per estimation increases. The swept sine frequency is kept constant for the specified periods. Less period yields slightly better control, but less stable and noisier amplitude estimates.
- With a compression factor 1 (left column of Figure 5), the control is unstable. But increasing the number of periods improves the situation. The best choice in this study is the middle plot (c=8, p=2), with a controller performance that respects the alarm lines.

This case study offers a new application perspective for the fuzzy FE method: it allows identifying the most robust controller settings for a given range of uncertainty of the controlled structural model.

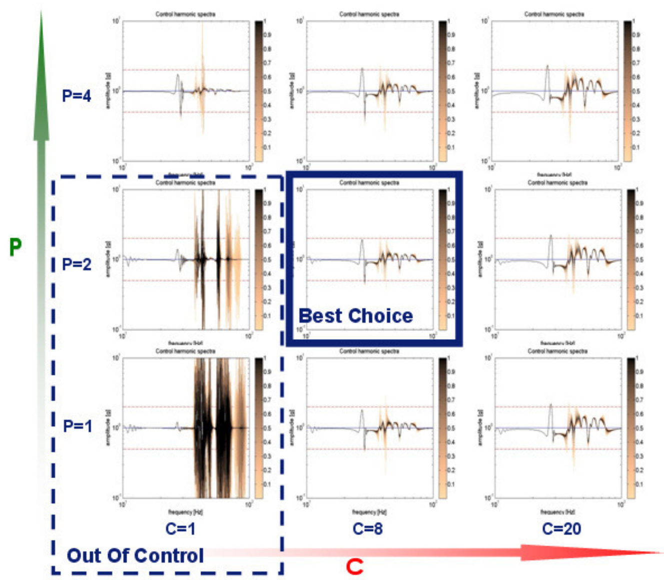

Figure 5: Virtual Shaker Testing: Uncertainty assessment of controller performance.

2.3 *Impact of non-linearity in the monitoring of vehicle suspension systems*

In the maintenance process of trucks and commercial vehicles, one critical component is represented by the damping systems. Some shock absorber monitoring methodologies has been developed and proposed in [19] in order to alert the driver whenever a maintenance or replacement of the shock absorber with considerable time and costs saving. All proposed methods use the information coming from in-vehicle sensors during normal road operation. Preliminary experimental tests have been performed on a passenger car to evaluate the usefulness and reliability of the methods. The test vehicle, properly instrumented by using laboratory and adapted in-vehicle instrumentation, has been tested upon two different experimental approaches to proof the monitoring concepts. An impact test took place in the laboratory of Fraunhofer LBF and a series of spectral tests were performed mostly on public roads.

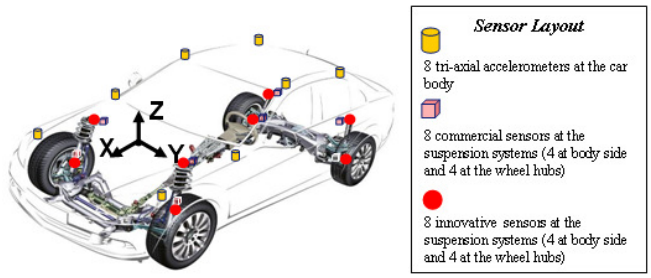

Figure 6: Sensors layout during the indoor and outdoor tests

The last-mentioned tests allow for the identification of the vibration behaviour of the vehicle in real operating conditions through an Operational or Output-only Modal Analysis (OMA). Both kinds of tests have been performed in two different shock absorber configurations (the testing vehicle was equipped with passive suspension systems at both axles). Firstly, four undamaged shock absorbers have been used while in the second test session one shock absorber (mounted at the rear-left suspension system) was replaced with a time-worn one.

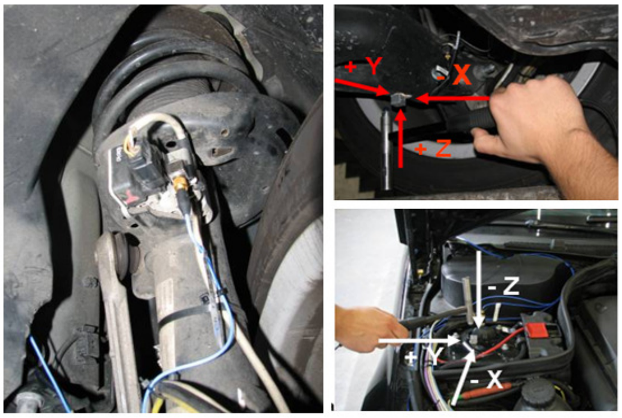

Figure 7: Example of an instrumented shock absorber (on the left). On the right, some excitation points adopted during the indoor tests are shown with the excitation directions highlighted.

The EMA (Experimental Modal Analysis) and OMA results obtained with two shock absorbers scenarios are compared in order to check the influence of the component life time on the vehicle dynamic behaviour. Nevertheless, taking into account both the results coming from EMA and OMA small discrepancies have been observed from the undamaged and time-worn rear-left shock absorber case in terms of eigenfrequencies and damping ratio values associated to the different vibration modes of the vehicle.

Therefore, for a real-time condition monitoring purpose, new methods using operational data and longer averaging intervals have been examined (for more details, see [9]). By the Experimental and Operational analysis, an interesting phenomenon has been observed for the same shock absorbers configuration. The eigenfrequencies values associated to the vehicle vibration rigid modes identified by EMA appear higher respect to corresponding ones obtained from OMA (Table 1). The comparison has been shown for the undamaged shock absorbers scenario.

A potential explanation could be found in the non-linear behaviour of the tire-suspension system. The friction phenomena present inside the shock absorbers and the bushing elements (and into the tire) could be so high that the energy introduced in the system (by a mid size excitation hammer) is not enough to overcome friction in the frequency range of interest bringing a no-well excitation of the vibration rigid modes of the car body. Furthermore a stiffening effect has been observed comparing the EMA with the OMA results.

Table 1: differences EMA and OMA

	EMA - Undamaged Shock absorber		OMA - Undamaged Shock absorber	
Mode	Eigenfrequency [Hz]	Damping ratio [%]	Eigenfrequency [Hz]	Damping ratio [%]
Heave	3.95	1.32	1.83	9.16
Pitch	4.69	3.50	3.21	4.65
Roll	6.83	2.32	5.29	2.13

This is more evident considering the auto-power spectrum relative to the same vertical acceleration (measured on the car body) for both kinds of tests and for the undamaged shock absorbers configuration. For the road input case, the energy delivered in the frequency band of interest is higher than those obtained by the indoor tests allowing a better excitation of the lower modes. Similar results have been obtained by Soria *et al.* in [9]).

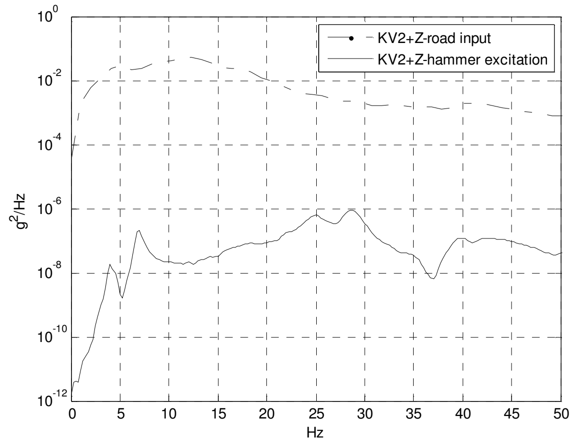

Figure 8: Example of autopower spectrum relative to one car body vertical acceleration for both kinds of tests and for the undamaged shock absorbers scenario.

3 CONCLUSIONS

This paper deals with the role and importance of uncertainties in different engineering design and test disciplines: crash and safety simulations, mechatronics system simulations and modal analysis. In real life systems, non-determinism is inherent component of the system model parameters, load conditions and the operational environment. Consequently, non-deterministic scatter characterizes any system's functional performance, which has important impact in the optimisation design process, design for robustness and system identification procedures. This paper investigates the impact of the uncertainty on some typical engineering problems. This includes a vehicle bumper subsystem optimisation study, the mechatronics system design challenge of a virtual shaker for satellites and condition monitoring analysis of a vehicle suspension system.

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