Model-Based Methodological Development of Active Suspension for Road Vehicles

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0 Abstract

In this paper a design cycle is described that makes it possible to create a reliable forecast model in accordance with an evaluation catalog for active systems as well as control structures which compare favorably to concepts implemented to date in terms of performance and robustness. By specifying a desired behavior, the controller can be calculated directly in one step. The model-based and analytical design core enables immediate application of the control concept to problems having the same structure. Furthermore, the concept provides a way of obtaining information for designing the passive properties of the system to be controlled. With the help of the reliable forecast model and parameter sensitivity analysis an online fault detection system can be realized. Development time can be reduced by means of the discussed approach.

1 Introduction

The significance of control systems in the automobile industry has been increasing at a rapid pace in recent years. The individual systems in use today include ESP (Electronic Stability Program), SBC (Sensotronic Brake Control) and ABC (Active Body Control [ABC99]). In future they will be combined with other systems in a vehicle, such as drive-by-wire, and interact with each other. These control systems are aimed at assisting and supporting the driver, enhancing comfort and making dangerous situations controllable for the driver.

In addition to the problem of designing each individual system, however, it is necessary to master the interaction between the active systems and in the ideal case make use of synergy effects. It is obvious that the design problems become increasingly complicated due to the large number of active systems. If one examines the conventional suspension design in extremely simplified form as the task of defining suspension and shock absorber characteristics, each active system involves numerous additional parameters and structural elements, all of which have to be defined with the same care as that already given to passive systems. Present-day suspension systems are thus considerably more complex in terms of their design problems than was the case in the past. When active systems additionally perform tasks critical for safety, even small errors must be ruled out completely.

This pushes up development input, expense and time, which is unacceptable in the current market situation. An approach already pursued to improve the situation is broad application of simulation tools for early support and provision of a sound foundation for the design process. However, design practice in reality shows that in most cases control systems are adapted and further developed in complex and costly driving tests “by hand”. Apart from the related time requirements, an interface problem must be expected between the development teams. On the one hand, the system designers who initially design the system on a rather idealized basis by means of simulation tools and, on the other hand, the application team that coordinates the system to series production concerns. However, this division of labor not only involves the already mentioned time problems, but also poses the risk that the systems drop in performance because the know-how frequently cannot be conveyed easily and smoothly between the teams. The respective control system as an “add-on” to existing hardware is viewed as another source of problems and thus synergy potential is not completely exploited.

Therefore, a solution must be provided in order to enhance design reliability already in the design phase to such an extent that subsequent coordination modifications are necessary only to a very limited degree.

This results in the following questions:

1. How great must the degree of detail of the simulation model be so as to enable reliable forecasts?
2. How are the relevant model parameters defined and how precisely must this be done?
3. What hardware parameters are critical, i.e. what parameters have a decisive influence on the behavior of the controlled system?
4. How great may parameter and structural uncertainty be without resulting in significant negative impacts on the active system?
5. How must the controller structure and parameterization be set up so the catalog of requirements to be defined for the total system is met and the remaining structural and parameter uncertainties pose no problems?
6. How can reliable online diagnostics and/or troubleshooting of the active system be designed? How can a malfunction therefore be detected rapidly and reliably?
7. Finally one has to examine the question of objective evaluation of the designed total system.

It is evident that in the ideal case it should be possible to tackle these problem areas entirely with simulation aids. This would require running through a mechatronic design and analysis process that gradually creates a reliable forecasting capability according to defined criteria and provides a means of designing and parameterizing control structures for these systems. An attempt shall be made here to design such a closed design cycle.

2 The Closed Design Cycle

In the following the individual steps for developing the closed design cycle will be discussed and quality gates defined that lead to a reliable design system for active suspension systems. The starting point in this approach is to draw up an evaluation catalog.

2.1 The Starting Point: The Evaluation Catalog

As the first step, an evaluation catalog must be set up for evaluating the total system. This evaluation catalog forms the basis for

1. the necessary modeling depth
2. the necessary controller structure
3. the resulting controller parameterization

Consequently key importance is attached to the evaluation catalog in the design process. The catalog is composed of two main components:

4. maneuvers or general loading conditions that representatively cover the field of boundary conditions to be met for the respective total system and
5. evaluation criteria that are decisive for assessing overall behavior under the defined loading conditions.

For example, different sections and driving maneuvers, such as

- rough road track
- ramp approach
- ...
- double lane change

could be defined as governing and be integrated into the evaluation catalog.
For evaluation purposes the following criteria, e.g.

- maximum roll angle
- vertical comfort assessed according to Frank [FRAN94] (Fig. 1) with the comfort coefficient $K = \int_{f=0}^{\infty} A_{\ddot{z}_A}(f) A_{B_1}(f)\,df$
- evaluated transversal head acceleration
- peaks in vertical acceleration on the passenger as a measure of the maximum peak of the body acceleration in a certain frequency range
- maximum actuator displacement
- wheel load fluctuations
- energy consumption

are defined and formally included in the catalog. Thus, the respectively defined evaluation variables result for each of the defined maneuvers. Altogether, therefore, $n \cdot m$ criteria result in the catalog, given n maneuvers and m evaluation criteria.

To underline the importance of the evaluation catalog, it should be pointed out that demands based on the evaluation catalog have a direct impact on the controller structure to be used. If, for instance, the ramp approach were defined here as a maneuver to be provided for, the control structure should not use an absolute body velocity for comfort control because a constant body velocity must be accepted by the control in the case of ramp approach. If this circumstance were ignored, this would lead to conflicts with the level control system, then resulting in substantial disadvantages in other maneuvers.

2.2 The Core of Design Quality: The Model

The core of the design process is the modeling of the system to be controlled. Initially the detailing depth of the model is defined on the basis of the experience of the development engineer. The elements of the model, by contrast, are defined by the evaluation catalog (Fig. 2) since, of course, all variables necessary for evaluation of the total system should be provided by the model. If, for example, axle vibrations are evaluated in the evaluation catalog, the model should deal with axle modeling in detail. If these axle vibrations do not play any role in the evaluation, a simplified model element can be used.

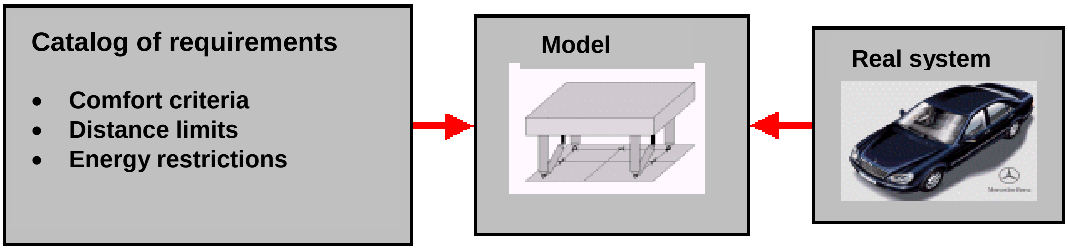

Fig. 2: Comfort evaluation function B1 for assessment of the vertical vibration sensation in the vehicle depending on the vibration frequency (seat taken into account)

A model for design has, for instance, the following structure (Fig. 3):

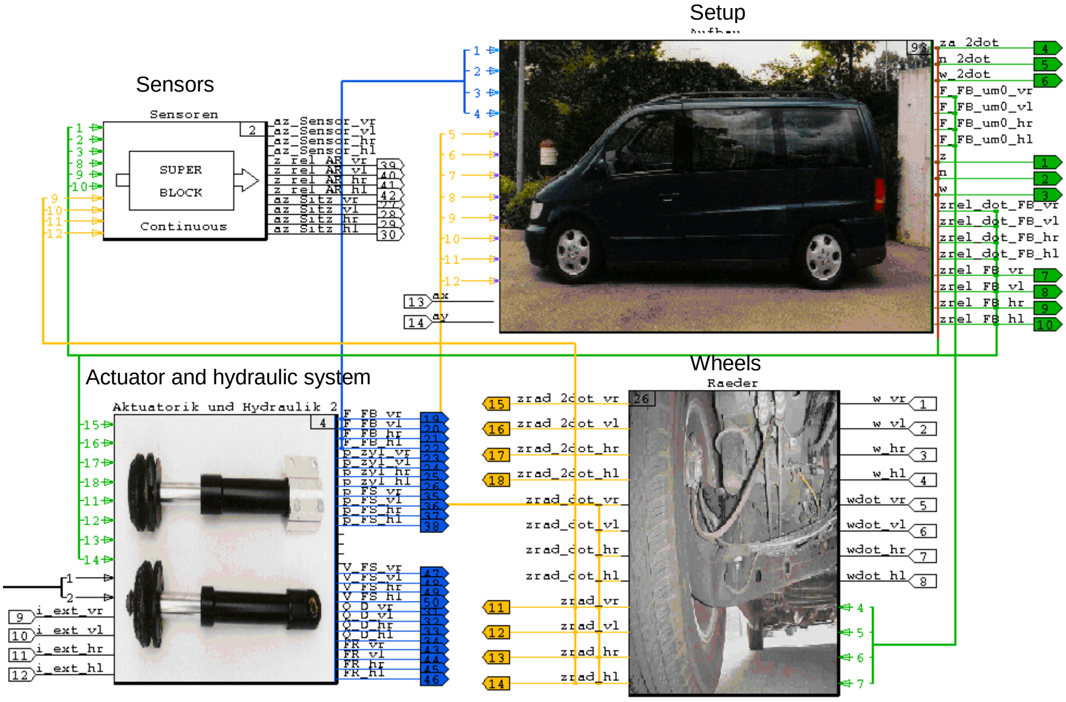

Fig. 3: Model structure in Matrixx [MATX96]

2.3 Quality Gate 1: Identification

At first the model set up has no verified quality, but merely reflects the experience horizon of the development engineer. To make reliable forecasts, the first step should be to perform parameter identification. If a prototype already exists in the ideal case, the model initially has to be subjected to parameter identification on the basis of measurements on the passive system. An identification algorithm according to Karmarkar [KARMAR84] has proven to be particularly effective here because, thanks to its completely vectorial method, it is also able to identify parameter numbers greater than 100 reliably, even for nonlinear systems. This algorithm has been significantly further developed through research work by DaimlerChrysler in the past years to such an extent that problems such as linear dependencies and non-identifiability can be detected and information on model quality can be provided to the user.

If the model is able to map a measurement typical for the system, the identification process must be repeated for different types of measurements that ideally correspond to the maneuvers from the evaluation catalog. At this point one can see whether the model is initially able to map all measurements equally (Fig. 4). If this is the case, the parameter spread that fundamentally results must be analyzed since a model can only provide reliable forecasts if all measurements can be mapped with a nearly identical set of parameters. The measure of the tolerable parameter fluctuations and thus uncertainty has to be made evaluatable in a further step.

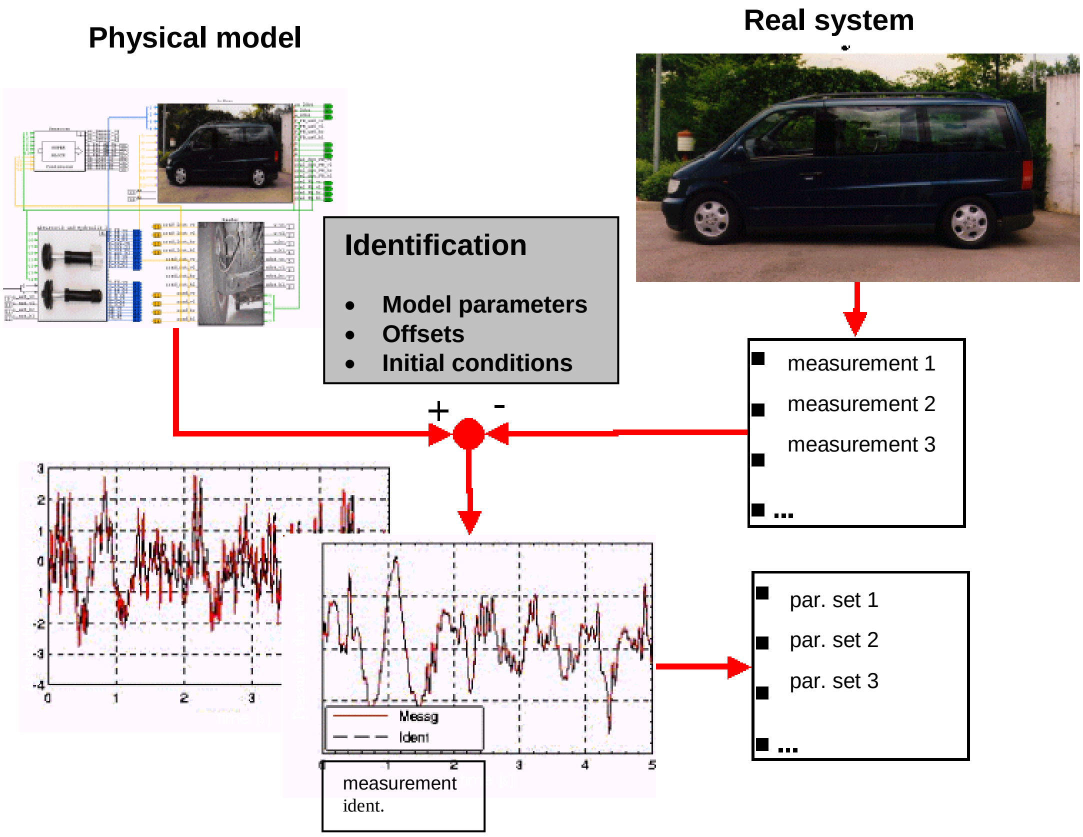

Fig. 4: Identification procedure via different measurements

2.4 The Control Concept

Now that a basic model structure has been defined through identification, the next step is to create the controller design on the basis of this model. Not only is the model structure itself explicitly inputted in the design, but also the requirements formulated in the evaluation catalog (Fig. 5).

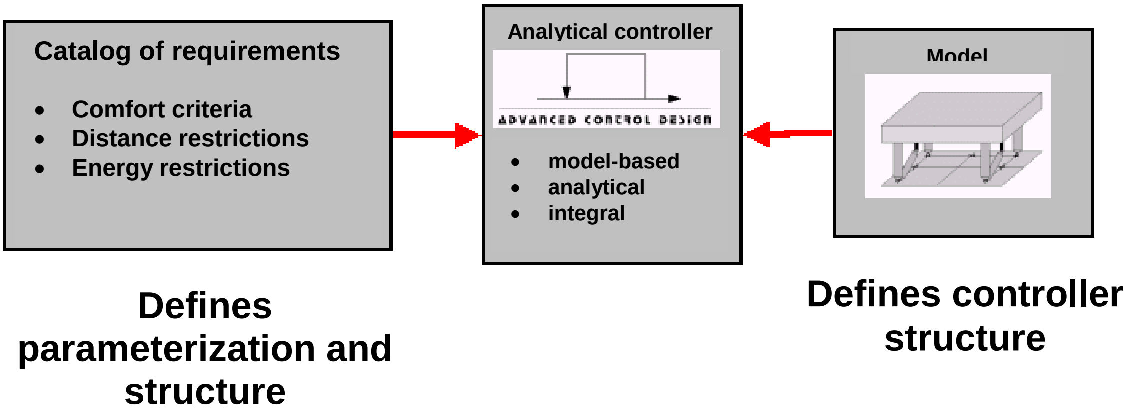

Fig. 5: Definition of the controller structure

The following consideration can be applied here:

> *All evaluation criteria formulated in the evaluation catalog should explicitly be found in the controller structure. If one wishes to go even further, one could extend the statement such that only these criteria may be inputted there.*

Among other things, the consideration may be motivated by an efficiency assessment: all input signals used in the control system tend to conflict or compete with each other[1]. Any reduction in conflict potential in the control structure, therefore, will increase the efficiency of the total system since fewer “compromises” have to be made. Consistent implementation of this consideration leads to exclusion of numerous variants. For example, cascade structures can be argued for on this basis only if system variables contained in the evaluation catalog can be monitored in the desired manner only in this way.

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1 [1]Otherwise input signals would be redundant

By virtue of the model-based design procedure, the method supplies a controller structure adapted to the respective system to be controlled, similar to state feedback controllers. However, this controller approach explicitly integrates dynamic elements, such as filters or integrators, and provides higher derivations of measurement variables automatically. In this way this control concept represents both state feedback control and observer at the same time. This, of course, results in a simplification of the design process[2]. Thanks to its integral, i.e. complete, structure, the controller monitors all characteristics of the system to be controlled and thus displays a high degree of robustness. This interrelationship is primarily due to the fact that the robustness of a controller depends for the most part on its structure and only secondarily on its parameterization. This may easily be motivated by the consideration that a controller which monitors all relevant system properties tends to react more robustly to fluctuations in parameters or system properties than a controller which leaves some relevant “peculiarities” of the system uncontrolled. In the past such complete controllers were realized only rarely because their complexity necessarily has to be oriented to the complexity of the system to be controlled. Consequently such controllers turn out to be significantly larger than with classical control approaches. As a result of advancements in computer technology, however, the scope of the control software is no longer restricted to the extent it was ten years ago. Therefore, such complete controllers encompassing the system are feasible with the current state of the art. Nevertheless, the question immediately arises as to how such control structures should be designed with a frequently large number of parameters. To solve this problem, a method was developed in recent years, which calculates the controller in one step through reverse computation, starting from a desired behavior of the whole system. We call this method “Advanced Control Design”.

A controller designed in line with the model in this way not only guarantees completeness and model conformity, but also a substantially improved applicability to problems of the same structure. Once a control variant has been determined, it can be applied to problems having the same structure. The definition of standard controllers is supported in this manner. From now on parameter and structural changes to the model that do not pertain to the order of the system to be controlled can thus be taken into account in the controller in one step. This gives the designer the necessary speed and flexibility to concentrate on the actual design task, i.e. the behavior of the closed control loop. Regarded in this fashion, the design of the controller is only indirectly the objective. Defining the resulting form, the “desired behavior”, is the actual task. This “desired behavior” is at the same time defined by a mathematical description that is intended to reflect the requirements of the evaluation catalog and must represent a feasible goal. On the one hand, the feasibility is aimed at the definition of the order of the control system for the targeted behavior since by using a controller, no systems can be realized that are smaller than the system to be controlled[3]. On the other hand, the resulting control parameterization also provides a starting point for the feasibility of the target. For instance, any arbitrarily “slow” system cannot be made out of a very “fast” system and would lead to a sign inversion

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2 [2] In the case of a complete state feedback controller and observer the separation theorem applies so the stability of the individual components is not influenced. However, the transient response to malfunctions is defined by both components so that, nevertheless, an iterative design proves to be necessary.

3 [3] More frequently, however, the resulting order of the entire control system is significantly greater due to the integration of dynamic elements into the controller, such as filters or integrators.

in the controller calculation and thus indicate infeasibility of the target. This feedback results in a very conscious consideration of the goals that should be achieved through the control system.

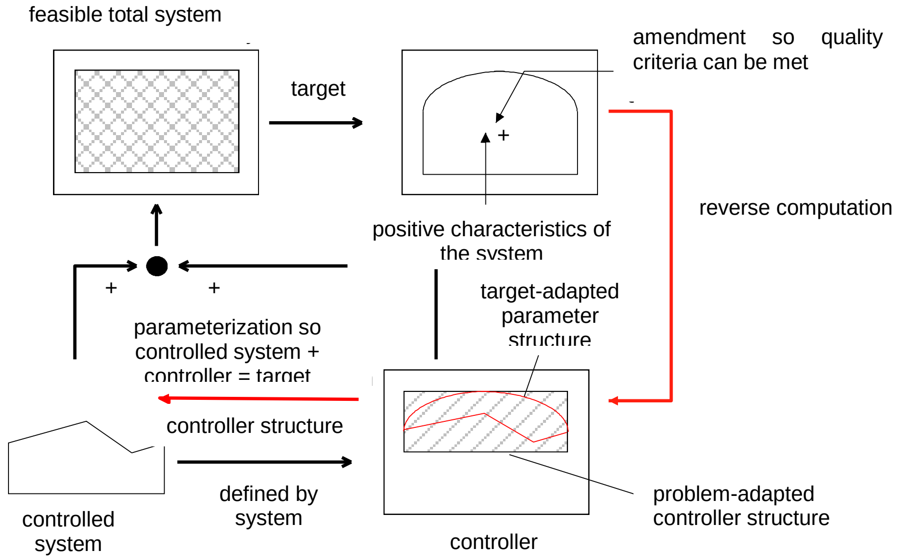

Fig. 6: Model-based controller design

The minimal structure of the desired behavior is thus defined by the system to be controlled and the requirement of completeness of the controller. Further structural elements can be used to map requirements of the evaluation catalog. This means the system and the controller structure together define the scope of the feasible options[4] (Fig. 6). Within the scope of the options defined in this way the system developer can define a desired behavior. At the same time it is necessary in accordance with the interaction of hardware and software that the characteristics of the passive system which are favorable in accordance with the overall behavior are integrated into the desired behavior. Merely the characteristics regarded as unfavorable should be replaced. The mechatronic concept that involves the interaction of hardware and software is again visible here. Although any wish can theoretically be met within the scope of the possible options, this may lead to hardware and software working against each other in the worst case. This not only has negative energy-related aspects, but also tends to lead to parameter-sensitive control systems and wear of components. If, for example, the natural frequency of the system to be controlled is already in the range planned for the total system, this system characteristic will be integrated into the target. This consideration may initially be a pointer that must be taken into account by the control designer, but at the same time it forms a bridge to the design of the hardware. In accordance with meaningful interaction of hardware and software, a further set of tools can be found here so as to design the passive system already in such a way that it “accommodates” the controller.

2.5 Quality Gate 2: Parameter Sensitivity Analysis (PSA)

Now that, on the one hand, a model is available whose inaccuracies are known from the identification and, on the other hand, a controller which has been analytically

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[4] 4 For example, only one P controller is required for complete monitoring of an integral-action element. A PT1 system, by contrast, needs a PI controller just to meet the requirement of completeness. Requirements for band limitations of the controller would make filters necessary which can be directly integrated into the controller design process in this way.

derived from the model structure and evaluation catalog, these model errors can now be evaluated and sensitivities examined. Overall the PSA ensures the forecasting reliability of the model, given successful analysis. The parameter sensitivity analysis is carried out on the total system (controlled system + controller) via simulation. Two criteria can be checked:

A) The relative sensitivities

Here one examines how sensitive the system generally is without taking into account the model quality. To do so, the parameter mean values taken from the identification series are shifted by a fixed percentage and inserted in the model. At the same time the controller parameterization is kept constant. By means of representative maneuvers, ideally with those from the evaluation catalog, the altered behavior of the close control loop is evaluated on the basis of the evaluation catalog and the criteria defined there, $K_j(p_i)$.

Then the relative reinforcement V_j of the criterion K_j regarding the shift of the parameter p_i by Δp_i can be defined by means of

$$V_j = \frac{K_j(p_i) - K_j(p_i - \Delta p_i)}{p_i - (p_i - \Delta p_i)} \cdot \frac{p_i}{K_j(p_i)} \quad \text{in the case of } K_i(p_i) \text{ and } p_i \neq 0$$

$K_j(p_i)$ and p_i define the criterion j and the model parameter i, using the set of parameters whose mean was taken from the identification series. It is plausible that a gain greater than 1 indicates a sensitive model parameter. Therefore, either

1. special care is necessary in determining the parameter or
2. the control structure must be designed more robustly taking special account of this problem or
3. a modification of the hardware is necessary or, if the gain represents an improvement in the criterion, an improvement of the overall behavior is possible by means of design-related measures.

An analysis of the relative sensitivity factors thus makes it effectively possible to improve the interaction between hardware and software and accordingly conforms with the basic concept of a mechatronic design process.

B) The absolute sensitivities

As the second criterion, the absolute change in the criteria from the evaluation catalog is determined in the case of a shift in the model parameters by the calculated parameter spread (Fig. 7).

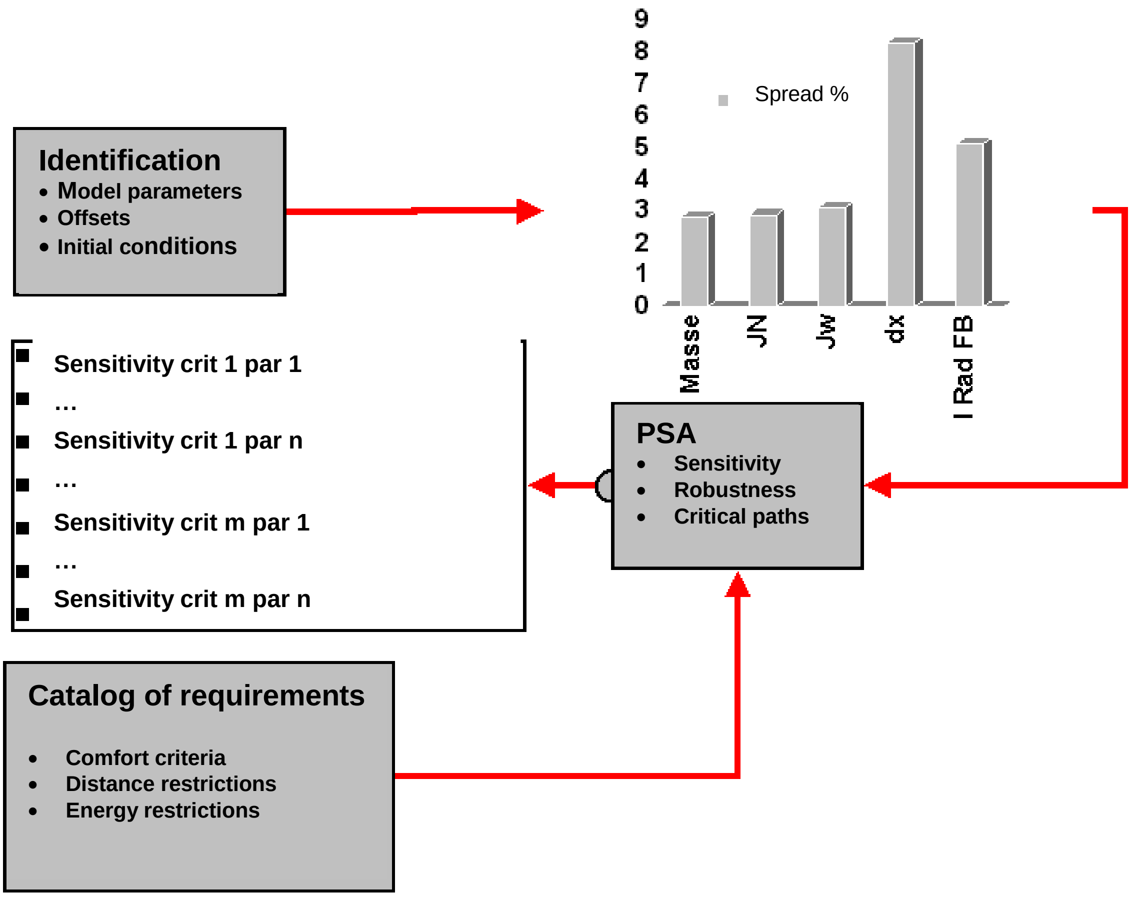

Fig. 7: PSA procedure according to B)

In this case the parameter mean values taken from the identification series are shifted by the determined parameter fluctuations and then inputted in the model. At the same time the controller parameterization is again kept constant. Evaluation is carried out similar to the analysis for relative sensitivity, i.e. the measure of the impact of model uncertainty is reviewed. If all evaluation criteria remain below the defined target barriers in this examination, one can assume that the model structure and parameterization found is “precise” enough with respect to the controller used. In this case the go-ahead can be given for controller release. If, on the other hand, individual target criteria of the evaluation catalog are not achieved in connection with the determined parameter uncertainty, either the model quality has to be increased or the controller must be designed to be more robust. Since the second variant must be achieved through a reduction in controller performance in most cases, improvement of model quality is advisable. This is meaningful also because a model improved in this manner improves system understanding and reveals problems that otherwise frequently remain concealed. Such a model improvement not only reduces model uncertainty, but also permits structural improvement of the controller. As a result, the model and its identification become the key to successfully implementing control systems with a higher degree of complexity in a short time.

2.6 The Circle is Closed: Implementation

In the following the controller is implemented in the target vehicle. Since especially nonlinear features that were not visible before may appear due to activation of the system, the design cycle should be run through once again below (Fig. 8).

Such a well-founded model now offers the opportunity, if deemed necessary, to carry out fine tuning of the controller by optimizing the desired behavior. However, frequently even the “basic design” will already display comparably favorable features in comparison to results that can be attained with conventionally designed controllers. As a result, a controller design that is robust, on the one hand, and can be applied immediately to systems having the same structure, on the other hand, is generated on a reliable forecast basis through this procedure. Generally, therefore, the work performed must only be carried out once and not be run through again for each target application. Renewed parameter identification here already provides all information required to design the controller in one step. A constant resulting desired behavior can be used as a distinguishing feature of the brand. In addition, platform concepts are possible. Thus, it is plausible that the benefits of this procedure are considerable.

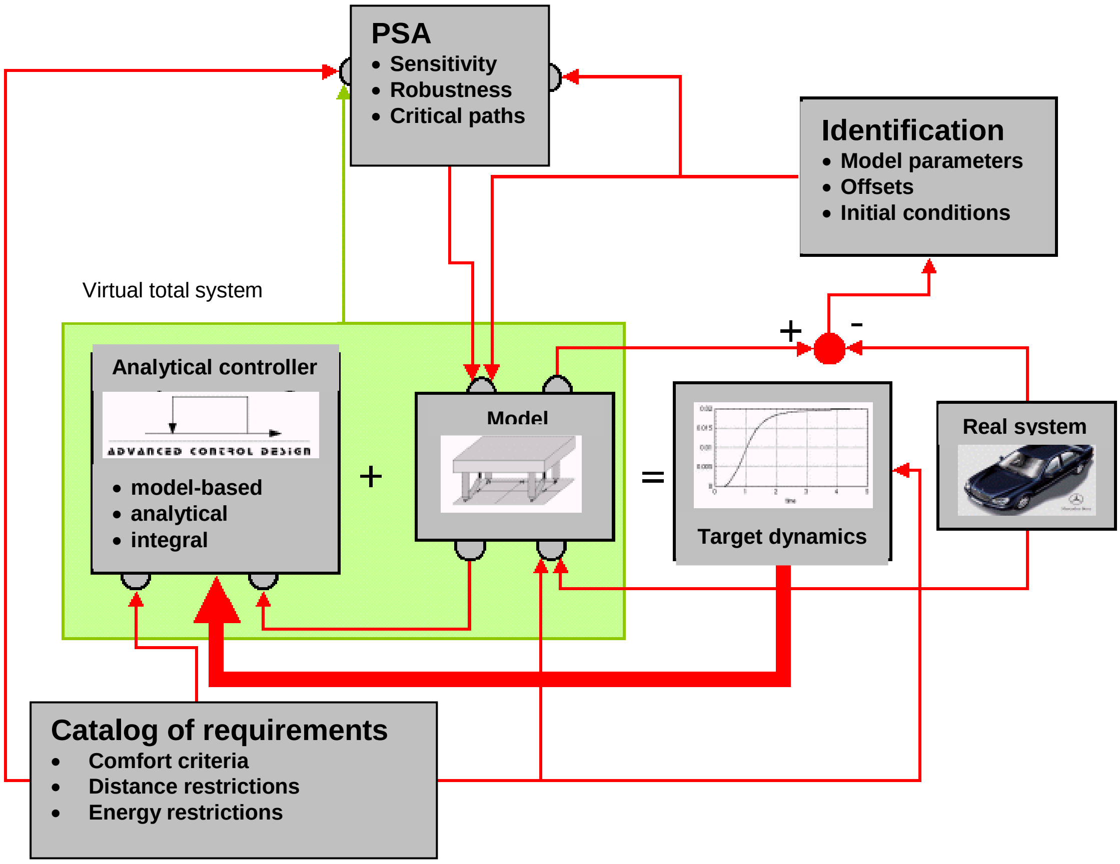

Fig. 8: Simplified representation of interrelationships and procedures of the closed design cycle. The model in the center.

2.7 More Safety Instead of Less: Online Diagnostics

A side product of this procedure is the capability of realizing model-based fault diagnostics. Here again the system model is the central element whose parameter uncertainty is known through the identification with different forms of excitation and load cases as well as the still tolerable system changes from the PSA. Similar to the way in which this is carried out offline in the case of parameter identification, an online representation of the model can be fed with measured values. The model then supplies expected output signals that are compared online with corresponding measured variables. Since it is known from the PSA how much the real system may deviate from the assumed behavior without this representing an error, error barriers can be defined for these deviations. If one of these error barriers is exceeded, this is a sure indication that there is an error. This procedure can also be justified by the consideration that the controller responds with expected behavior only as long as the assumed model structure and parameterization correspond to the real system within the framework of the previously defined error tolerances. A key factor here is that such a fault detection system can detect a failure much earlier than frequently used limit value monitoring systems. This may provide the system with a decisive time advantage to be able to react to a failure at an early stage. If different formulations of the model or subsystems of the model are examined parallel to each other, fault diagnostics are even possible [STREIT01]. If, for example, the submodel of actuators does not supply any faults while the complete model detects a fault, the cause of the fault can already be defined in this way. A diagnosis of “action groups” can take place in a targeted fashion through even finer division of the complete model so the response to the failure can depend on the situation. For instance, failure of the acceleration sensors may absolutely be critical in the structure of a vehicle with active suspension, but can be cushioned by early changeover to a purely displacement control concept. The customer could continue to drive without any problems and have the fault eliminated in the new repair shop, without ever getting into a critical situation. In this way treatment of the frequently discussed safety problem of active systems can be simplified. The “intelligence” in the vehicle makes failures easier to detect and thus the total system safer.

3 Implementations

A model-based variant of the ABC system was developed in a very early phase of development of this design process (Fig. 9). Only a rudimentary notion of the design process and a preliminary variant of the present model-based control design core existed at that time [STREIT96].

Fig. 9: ABC with Advanced Control Design

In the following years the theory on the present-day design cycle was refined and put into practice in a rail vehicle for the high-speed train [STREIT01]. The objective was to implement a lateral comfort control by means of two lateral actuators.

Fig. 10: Model-based lateral comfort control for high-speed trains on a dynamometer in Munich

The controller was implemented in only 18 months and tested on a roller-type dynamometer [ROLLP85] in Munich (Fig. 10). The client, Bombardier, is working on series implementation.

Recently studies on active suspension systems in the van sector were expanded and hydropneumatic actuators were employed that bring about design space advantages, on the one hand, and enable scaling concepts, on the other (Fig. 11).

Fig. 11: Model-based comfort control in V class with hydropneumatic suspension struts. Comparison between passive (left) and active (right) while cornering

Here again the described design cycle was used. At first a model of the structure was set up, as shown in Fig. 3.

Parameter identification was then carried out on measurements of the prototype. Fig. 12 shows the calculated parameter spreads over six different measurements. Accordingly the greatest uncertainty exists in the center-of-gravity position in the x direction.

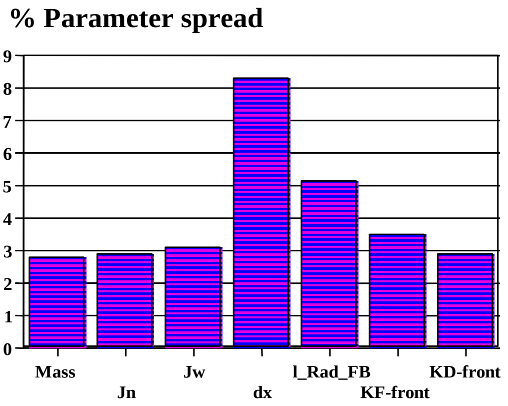

Fig. 12: Percentage parameter spread in various measurements.

The relative sensitivity analysis shows that the vehicle mass is a critical parameter (Fig. 13). The controller was then designed adaptively with respect to changes in mass.

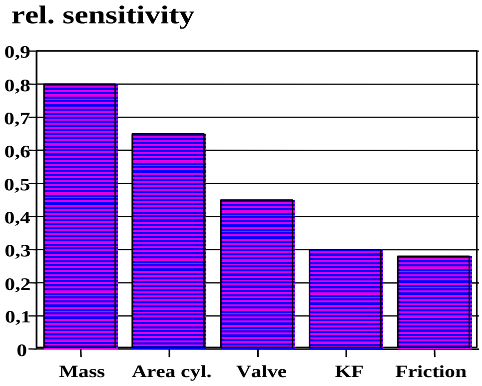

Fig. 13: Relative sensitivity

Overall, significant improvements result from the control in the comparison between the active and passive system (Fig. 14).

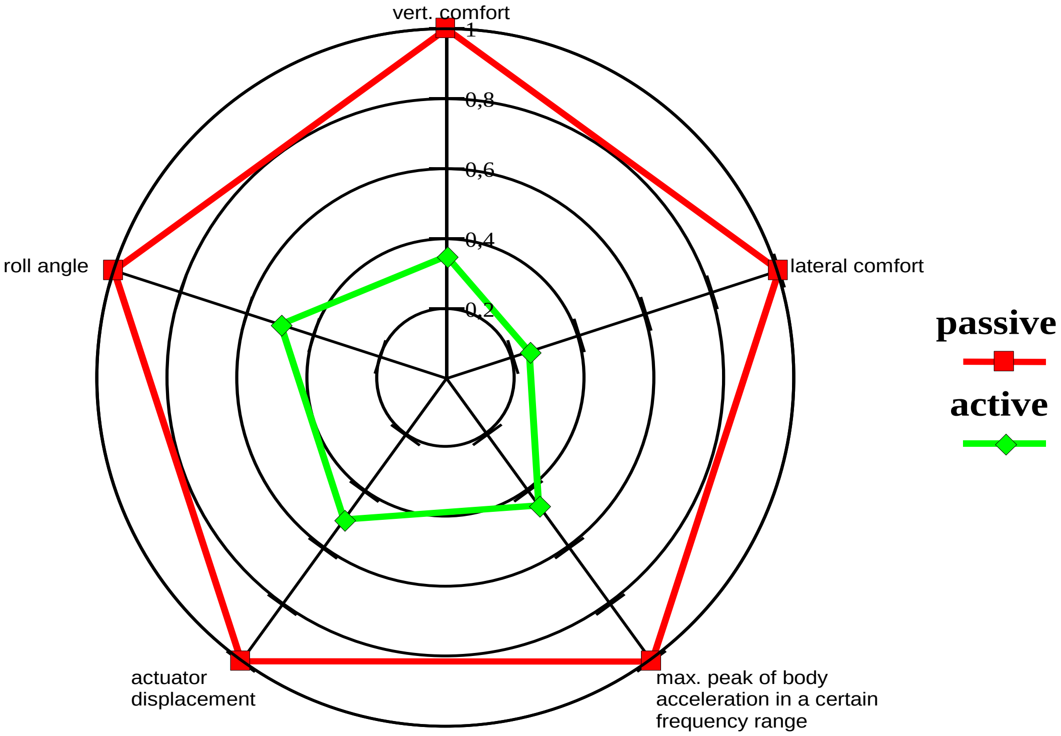

Fig. 14: Standardized comparison between active and passive operation.

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