INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

SIMULATION OF AN ADAPTIVE ER DAMPER SUPPORTED BY AN EFFECT-CATALOG

M. Kahlert, A. Iriondo and W. Schweiger

Keywords: early stages of design, effect-catalog, simulation, damper, electrorheological fluid (ERF)

1. Introduction

In the early stages of design the computer-aided modelling support is still insufficient. One problem in the development of innovative solutions is the absence of an adequate support tool. An effect-catalog will therefore be introduced as a solution for this gap. The effect-catalog is filled with information about widely unknown and physically interesting effects. This catalog is a continuous application system which enables the search of the adequate material for a specific construction problem. It offers the required material equations and, if desired, it simplifies the further calculation as it provides a simulation block for each particular material equation [Kahlert 2003]. A semi active suspension system including an adjustable electrorheological damper will be considered in order to explain the use of this effect-catalog. To simulate the modeled system, the simulation tool MATLAB/Simulink is used.

2. Effect-Catalog

Catalogs are a commonly used tool in engineering design. Indeed, there are different types of catalogs known, which cover a range of solutions, depending on the current design stage. They support the engineer by giving information on, e.g. possible bearings, materials, etc...

There is a good support for the engineer in later stages of design; however, it is not enough in the early stages. It is important to offer support also in the early stages of design, in which only few information about the construction exists. To close this gap of information, a new type of catalog is proposed. Its aim, beside the support in early stages, is to provide new research results and innovations, especially for disciplines like mechatronics, adaptronics, mechanics and so on. Here it is necessary to use modern techniques like the internet to keep the content of the catalog up to date. Therefore a client-server-architecture is useful, where the catalog operates as a client on the engineer's computer and the database is then placed on a central server, which can be easily expanded with new effects.

The basis of the catalog is the constitutive theory, which enables the connection of variables from different disciplines like electrodynamics and mechanics. The advantage is a common description of discipline spanning effects. Most design engineers are not familiar with many of these effects. Such a catalog will offer the possibility to look for formulas and effects in order to cover the given problem interdisciplinary an, hence, entirely.

In general the catalog works as follows: The user knows which variables he wants to combine. In a dialog he selects the variables and the program starts searching the database, whether an effect is known, which combines the requested variables in one equation. In this case a new page opens, containing further information to the equation, giving examples and rules for using this formula exemplary.

If no precise information about variables exists, a search for keywords is also possible. The developer will get informed about various possibilities and new materials that are offered. But how does such a material look like? An example is an electrorheological fluid (ERF). Interestingly, this material can vary its viscosity from liquid to solid. This is induced by an electric field, which subsequently changes the viscosity. This kind of materials can be described using different equations. One is the Bingham-model:

$$\tau = \tau_0 + \eta_P \dot{\gamma}\,,\ \tau_0 = \alpha \cdot E^2 \tag{1}$$

The catalog will offer this equation and a description of the equation's variables and constants. Boundary conditions, e.g. in which range the viscosity can vary, are also given. An ERF works as follows. ERF react to an applied electric field respectively with a variation in their theological properties (yield stress, plasticity and elasticity) and consequently their theological behavior. The magnitude of the viscosity of these fluids can be specifically influenced and the strength of material can reach values up to 130kPa [Wen 2003]. They will get from liquid to solid due to the electric or magnetic field. The changes in their viscosity are reversible; the original rheological properties are restored when the field is removed. These materials contain suspension particles (such as polymer, metal or dielectric) suspended in an inert fluid (such as silicone, mineral, or some other oil). If a voltage is impressed on it, the particles build up chains along the electric flux lines. The chains are built up for sufficient electric field strength and particles concentration (weight proportion of 30-50%) and which impede the motion of these particles and consequently the flow.

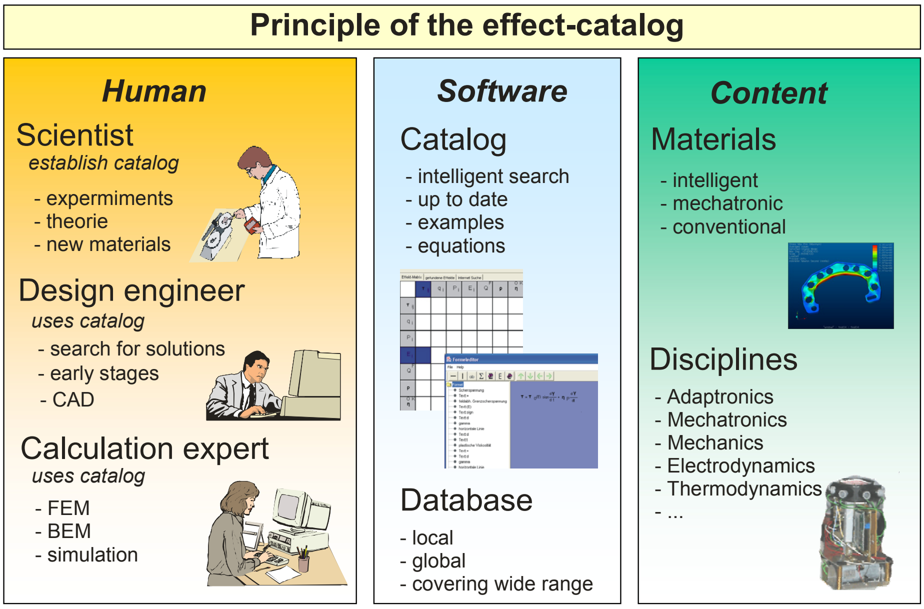

Figure 1. Interconnection in the effect-catalog

3. Dynamic Model of the quarter car

The purpose of a suspension system is to guarantee comfort by isolating the vehicle from the road disturbances, and to achieve security by maintaining the traction force between the tire and the road surface [Mitschke 1997]. Passive suspension design is a compromise between security and comfort. A high damping provides stability and ride security. However, it transfers the road excitations notably, which leads on the other hand to a low ride comfort. The characteristics of springs and dampers in a passive suspension system are fixed. These are chosen according to the intended application [Yokohama 2001].

The damper of an active suspension is able to add and dissipate energy from the system. The problem of an active suspension system is that it requires an external energy source to adjust the required

damping. A semi active system determines the level of damping based on a control strategy in order to obtain the comfort and security desired. One of the most common semi active control policy is skyhook control [Yao 2002, Choi 2000].
In this paper a semi active suspension system including an adjustable ER damper will be considered in order to explain the use of the mentioned effect-catalog.

3.1 Model of the quarter car

In this analysis a simple quarter car model with a semi active control strategy is chosen to simulate the suspension system (Figure 2). This is a two-degrees-of-freedom system with the sprung mass m_S which represents the mass of the chassis and the load, and the unsprung mass m_U which represents the tyre mass. The stiffness of the suspension and the tyre are represented by c_S (stiffness attached to the sprung mass) and c_U (stiffness attached to the unsprung mass) respectively. The damping of the suspension is here represented by k_S. The road excitation which depends on the simulation's time is represented as r(t). In this simulation we will introduce three different kinds of road excitations. This will be described as $r_1(t)$, $r_2(t)$ and $r_3(t)$ and will be explained later.

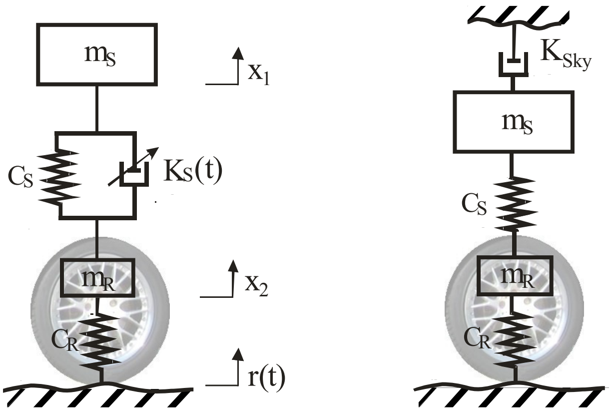

Figure 2. Quarter car Model

$$\dot{x}_1 = x_2 \tag{2}$$

$$\dot{x}_3 = x_4 \tag{3}$$

$$\dot{x}_2 = \frac{-k_S}{m_S}(x_2 - x_4) - \frac{c_S}{m_S}(x_1 - x_3) \tag{4}$$

$$\dot{x}_4 = \frac{k_S}{m_U}(x_2 - x_4) + \frac{c_S}{m_U}(x_1 - x_3) + \frac{c_U}{m_U}(u - x_3) \tag{5}$$

These equations can be written in matrix form as a state space:

$$\dot{X} = AX + Bu \tag{6}$$

where $X = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-c_S}{m_S} & \frac{-k_S}{m_S} & \frac{c_S}{m_S} & \frac{k_S}{m_S} \\ 0 & 0 & 0 & 1 \\ \frac{c_S}{m_U} & \frac{k_S}{m_U} & \frac{-c_S - c_U}{m_U} & \frac{-k_S}{m_U} \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{c_U}{m_U} \end{bmatrix} \tag{7}$$

and u is the road excitation $r_1(t)$, $r_2(t)$ or $r_3(t)$. In order to adapt the suspension described above to the road conditions, an adjustable damping $k_S(t)$ will be necessary.

3.2 Adjustable damping

The damping force is the result of the friction of the damper-fluid flowing through an orifice. The level of the damping force can therefore be adjusted by varying the orifice area in the damper (as in the case of semi active hydraulic dampers) or by changing the viscosity of the fluid using controllable fluids. Electrorheological (ER) fluids belong to this type of fluids [5]. Their viscosity can be varied very fast by applying different levels of electric or magnetic fields respectively [Vessonen 2003].
As we look for an adjustable damping $k_S(t)$ in an effect-catalog, the material equations for this kind of fluids may not include the damping, but the τ as in Equation (1). It is $\tau = F_D/A$, where A is the orifice area in the damper and the damper force is $F_D = k_S \cdot v_{rel}$. This could be a way to get the damping k_S.
Apart from material equations, it is possible to get a table of values for different ER dampers, which includes the damper force for different electric fields and relative velocities. These tables also include finished simulation blocks which can be just added to the simulation.
The complete material block given by the effect-catalog should be inserted in the model of the quarter car before running the simulation. Apart from the material block (damping block) we also need an appropriate control law, which decides the appropriate electric field in the current condition.

3.3 Sky-hook control

One of the best known semi active controls is the sky hook control law. This control law, introduced by Prof. Karnopp in 1974, is an easy way to control vibrations. The objective of this control law is to isolate the vibrations of the sprung mass, as well as to avoid high relative motion between sprung and unsprung mass [Ronald]. The sky hook control law can be described using equation (8).

$$x_2 \cdot v_{rel} \geq 0,\ E = E_{\max} = 5kV$$

$$x_2 \cdot v_{rel} < 0,\ E = E_{\min} = 0kV \tag{8}$$

In skyhook control, the damper is controlled by two damping levels: the high-state and low-state damping. The determination of whether the damper is to be adjusted to either its high state or its low state depends on the product of the relative velocity between sprung mass and unsprung mass and the absolute velocity of the sprung mass. If the product is positive or zero, the damper is adjusted to its high state; otherwise, the damper is set to the low state. When the ER damper is adjusted to the high-state, the electric field is set to 5 kV, when the ER damper is supposed to be adjusted to the low-state, the electric field is set to 0 kV. This law acts as follows: when the sprung mass moves up (the velocity of the sprung mass is positive) and the sprung and the unsprung masses are getting closer (the relative velocity v_{rel} between both masses is negative), the damper force should be zero. In order to get a zero damping force the damper should be able to bring energy in the system. This is not possible for semi active dampers, wherefore the damper is adjusted to the low state [Vessonen 2003]
When the sprung mass moves down (the velocity of the sprung mass is negative) and both masses are being pushed together (the relative velocity v_{rel} between both masses is negative), the damper force

should be infinitely big in order to push up the sprung mass. An infinite damping is physically not possible, wherefore the damping is adjusted to the high-state.

3.4 Road excitations

We can test our quarter car model on different road excitations. We chose here a sine excitation (r_1), a bump (r_2), and a stochastic excitation (r_3). For the sine excitation we chose a frequency from 1 Hz and 10.5 Hz, which are the natural frequencies of the sprung and unsprung mass, and an amplitude A=0.015 m. For the bump we chose a bump-high $h_B = 0.04$m, and for the stochastic excitation a Gaussian noise.

4. Simulation and Results

The simulation is carried out with SIMULINK of MATLAB®. The whole quarter car system consists of four subsystems: the quarter car model, the damping block, the controller and the road excitation. These are connected as in Figure 3.

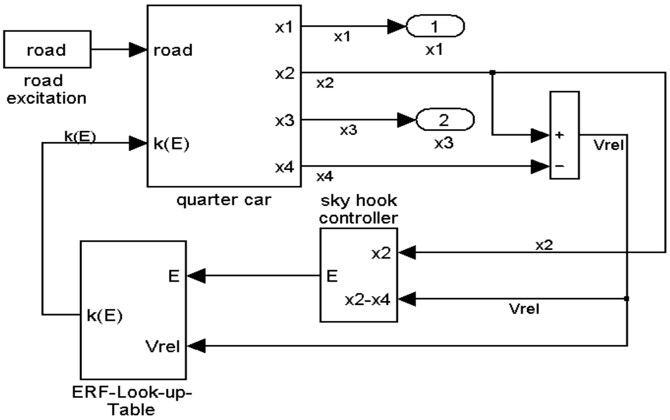

Figure 3. Simulation of the complete system

For the comparison a passive damper is also applied to the simulation to compare the results of the semi active damper. Furthermore we assume that the ER damper responds with a time delay of 10 ms which is introduced in the damping system. The parameters used in the simulation of the quarter car model are listed in table 1.

Table 1. Simulation parameters

Simulation values	
Sprung mass	m_S=400 Kg
Unsprung mass	m_T=40 Kg
Suspension stiffness	c_S=15 800 N/m
Tyre stiffness	c_T=158 000 N/m

After running the simulation for the different road excitations, an improvement of the oscillation's behavior is shown by all three road excitations using the sky hook control. The sine excitation was used by an excitation frequency of 1 Hz and 10.5 Hz. For the passive damper, the sprung mass displacement (x_1) oscillates with an amplitude, which is much higher than the road excitation. Using the sky hook control, the amplitude of the sprung mass displacement (x_1) was satisfactory minified. Using the 10.5 Hz sine excitation by a passive damper and a sky hook control it shows similar results for the unsprung mass displacement (x_3).

The second and the third road excitations are a bump and a stochastic excitation. A passive damper needs a quite long time to fade away the excitation after hitting an obstacle or oscillates for a short time but at high amplitude, depending on the chosen damping. Using a sky hook control it is possible to obtain a short time oscillation by low amplitude. Figure 4 shows the suspension travel response of the sprung mass for a passive and a semi active damper including the road excitation r_1.

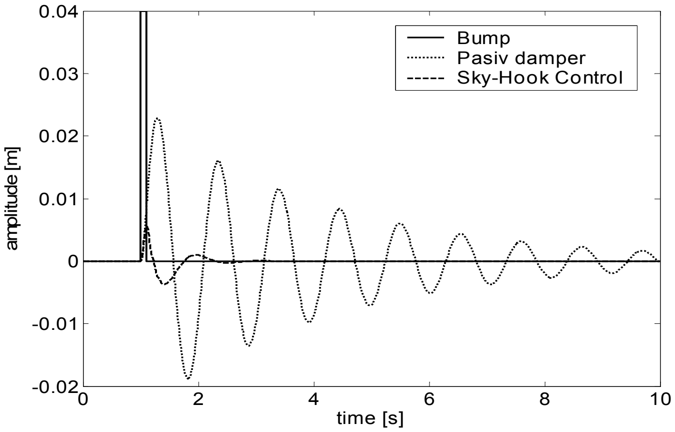

Figure 4. Comparison between passive and semi active Damper for the bump excitation

5. Key conclusions

Using an effect-catalog for the design of a semi active damper simplifies the search of the appropriate fluid. The respective mathematical equations of ER fluids, as well as all the necessary coefficients, or tabulated experimental results are stored in the database of the catalog for different fluids. Besides the mathematical equations and the results´ tables, the Effect-catalog provides you with links to Simulink materials blocks, which have already been saved, as well as the MATLAB-commands for the defined coefficients of the selected fluid equation. The Simulink-material-blocks are easily inserted in the simulation. After running the simulation an improvement of the sprung mass oscillation behavior is definitely shown.

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Michael Kahlert, Simulation of an adaptive ER damper supported by an effect-catalog
University of Erlangen-Nuremberg, Institute for Engineering Design
Martensstr. 9, 91058 Erlangen, Germany
Telephone: +49 9131 85-23216, Telefax: +49 9131 85-23223
E-mail: kahlert@mfk.uni-erlangen.de