An object oriented data model for vehicle dynamics problems

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SYNOPSIS The design of automotive systems using computer codes for vehicle dynamics problems features cost reduction and quality enhancement. This paper presents two basic approaches. The first approach deals with the application of CAD data bases to the evaluation of input data for multibody system formalisms, most adequate for automotive system modelling. An object oriented data model for multibody systems is presented. The second approach covers the development of an integrated simulation tool for automotive vehicles and the corresponding animation facilities. As an example the dynamical analysis of a van is shown including the choice of optimal suspension parameters.

1 INTRODUCTION

Increasing competition within the automotive industries results in a large variety of automobiles to be developed in shorter and shorter periods. Thus, the classical method of automobile design via intensive experimental testing of prototypes is no longer economically feasible. Therefore, the dynamical behaviour of a vehicle has to be simulated during the development process simultaneous with the overall design of the automobile.

The dynamical analysis of a vehicle system is characterized by

- modelling as a multibody system,
- generating the equations of motion,
- simulating the trajectories of the generalized coordinates,
- animating the vehicle system by moving pictures and
- evaluating the dynamical performance by adequate criteria.

Related to the dynamical analysis are the following computational aspects:

- CAD software for the modelling,
- CAE formalisms for generation of equations,
- ODE and DAE integration codes for simulations,
- computer graphics for animations and
- signal analysis and optimization codes for evaluation of the performance.

For the dynamical analysis a unique description of all the elements of a multibody system is required. Using an object oriented software approach, the data of multibody systems elements are defined independently of the formalism applied for the generation of equations of motion. It has been proved that symbolically generated equations of motion are computationally more efficient than numerically derived equations of motion as shown by SCHIEHLEN and KREUZER (1), SCHAECHTER and LEVINSON (2), SAYERS (3), and LEISTER (4). High efficiency is achieved not only for time integration during simulation but also for parameter variation during optimization or sensitivity analysis, respectively. The formalism NEWEUL will be presented in detail.

Automobiles are highly nonlinear dynamical systems which may be investigated by numerical simulation or by linearization techniques resulting in eigenfrequency analysis. For the numerical simulation the available integration codes have to be thoroughly tested and implemented in software packages. Usually more than one code is required to handle all the different problems in vehicle system dynamics. The choice of the computer code may be made by the user or the software system, respectively. Due to the nonlinearity the simulation results show usually very irregular or chaotic motions. Then, signal analysis techniques from nonlinear dynamics have to be included in the investigation. This is also true for the strength evaluation requiring stochastic methods from material sciences.

2 MULTIBODY SYSTEMS MODELLING

Road vehicles can be modelled properly as multibody systems for the design and the analysis of components like suspensions, attitude controllers, shock absorbers, springs, mounts and steering assemblies as well as brakes and antiskid devices. The complexity of the dynamical equations called for the development of computer–aided formalisms a quarter of a century ago. The theoretical background is today available from a number of textbooks e.g. ROBERSON and SCHWERTASSEK (5), NIKRAVESH (6), HAUG (7) and SHABANA (8). The state–of–the–art is also presented at a series of IUTAM/IAVSD symposia, documented in the corresponding proceedings, see, e.g., KORTÜM and SCHIEHLEN (9), BIANCHI and SCHIEHLEN (10), KORTÜM and SHARP (11).

In addition, a number of commercially distributed computer codes was developed, a summary of which is given in the Multibody Systems Handbook (12). The computer codes available show different capabilities: some of them generate only the equations of motion in numerical or symbolical form, respectively. Some of them provide numerical integration and simulation codes, too. Moreover, there are also extensive software systems on the market which offer additionally graphical data input, animation of body motions and automated signal data analysis. There is no doubt that the professional user, particularly in the automotive industry, prefers the most complete software system for dynamical multibody system analysis.

2.1 Elements of Multibody Systems

The method of multibody systems is based on a finite set of elements such as

- rigid bodies and/or particles,
- bearings, joints and supports,
- springs and dampers,
- active force and/or position actuators.

For more details see ROBERSON and SCHWERTASSEK (5) or Ref. (13). Each vehicle can be modelled for dynamical analysis by these elements as a multibody system, Figure 1.

The elements have to be characterized by body–fixed frames, Figure 2. Then, the absolute and relative motion are defined by the frame motion using the kinematical quantities of 3x1–translational vectors **r** and 3x3–rotation tensors **S**. The description of joints, Figure 3, requires two frames, one on each of the connected bodies. The joints constrain the relative motion between two rigid bodies, and as a consequence, reaction forces have to be considered.

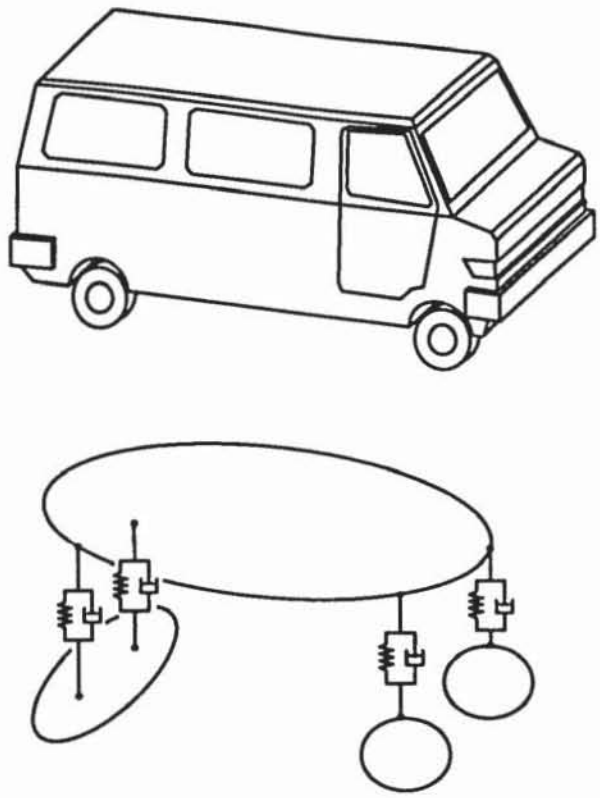


Fig 1 Multibody model of vehicle

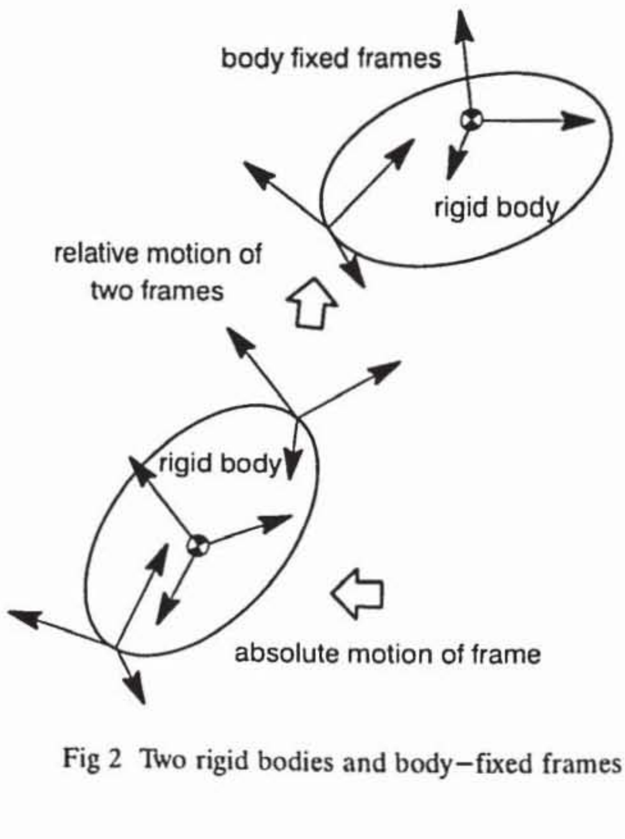


Fig 2 Two rigid bodies and body–fixed frames

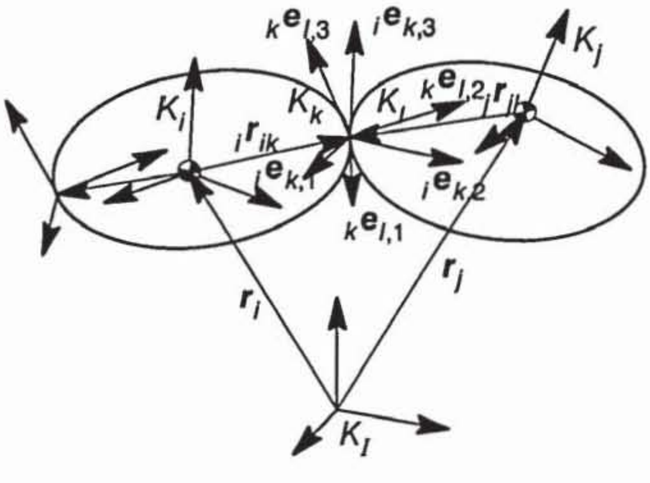


Fig 3 Joint between two rigid bodies

2.2 Multibody System Datamodel

The German Research Council (DFG) sponsored by a nationwide research project the development of a multibody system datamodel. In this project 14 universities and research centres have been engaged and all of them agreed on the datamodel, see Ref. (14).

The datamodel has been defined as a standardized basis for all kinds of computer codes by OTTER, HOCKE, DABERKOW and LEISTER (15). The following assumptions were agreed upon:

1. A multibody system consists of rigid bodies and ideal joints. A body may degenerate to a particle or to a body without inertia. The ideal joints include the rigid joint, the joint with completely given motion (rheonomic constraint) and the vanishing joint (free motion).
2. The topology of the multibody system is arbitrary. Chains, trees and closed loops are admitted.
3. Joints and actuators are summarized in open libraries.
4. Subsystems may be added to existing components of the multibody system.

A multibody system as defined is characterized by the class *mbs* and consists of an arbitrary number of the objects of the classes *part* and *interact*, see Fjgure 4.

The class *part* describes rigid bodies. Each *part* is characterized by at least one body−fixed *frame*, it may have a mass, a centre of mass and a tensor of inertia summarized in the class *body*, Figure 5.

The class *interact* describes the interaction between a frame on *part a* and a frame on *part b*. The interaction may be realized by a joint, by a force actuator or a sensor resulting in the classes *joint*, *force* or *sensor*, respectively. Thus, the class *interact* is characterized by two types of information: the frames to be connected and the connecting element itself, see Figure 6.

The presented classes are the basis of the class *mbs* which means the assembled vehicle. The model assembly using the datamodel is now easily executed. Figure 7 shows the whole procedure. According to the definitions, the datamodel represents holonomic, rheonomic multibody systems.

The data model defined can be easily applied by the object−oriented multibody modelling kernel DAMOS−C, see DABERKOW and SCHIEHLEN (16). Then, information on the parameters of the multibody system can be extracted from commercial CAD−systems, see Figure 8. Another possibility is the application of the database RSYST as shown by OTTER, HOCKE, DABERKOW and LEISTER (15).

3 GENERATION OF EQUATIONS OF MOTION

The multibody system model has to be described mathematically by equations of motions for the dynamical analysis. In this chapter the general theory for holonomic systems will be presented using a minimal number of generalized coordinates for a unique representation of the motion.

3.1 Kinematics of Multibody Systems

According to the free body diagram of a vehicle system, firstly, all constraints are omitted and the system of p bodies holds 6p degrees of freedom. The position of the system is given relative to the inertial frame by the 3x1−translation vector

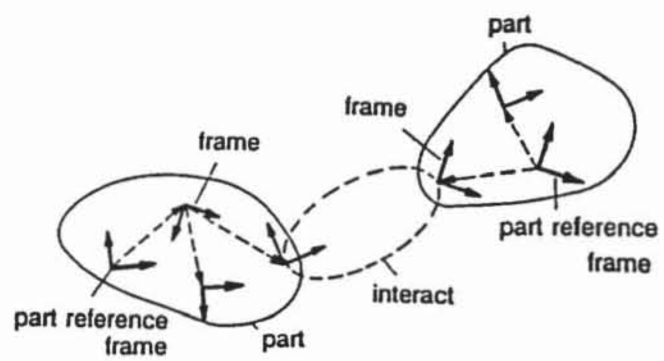
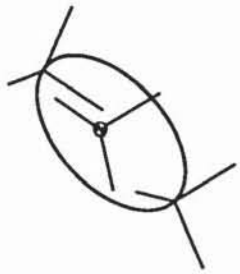


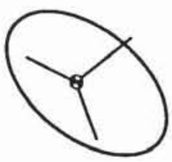
Fig 4 Multibody system to be represented by the datamodel

Technical system | multibody model | class description



class: part		
name	class	description
body	body	mass properties of part
frame	FRAME	frames on the part

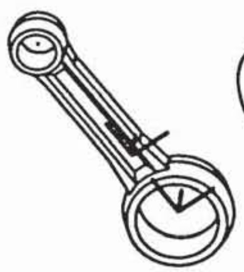
Technical system | multibody model | class description | object of class

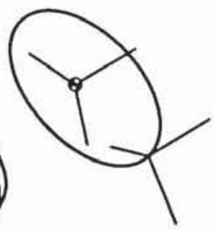


class: body		
name	type	description
mass	dparam	mass of body
mframe	name	c.o.g frame
inertia	dparam(6)	inertia tensor
iframe	name	tensor frame

object: body1	
name	component
mass	M1
	0.418
mframe	' '
inertia	I11,I22,I33,I12,I13,I23
	113.0,1296.49,1380.67
iframe	' '

Technical system | multibody model | class description | object of class

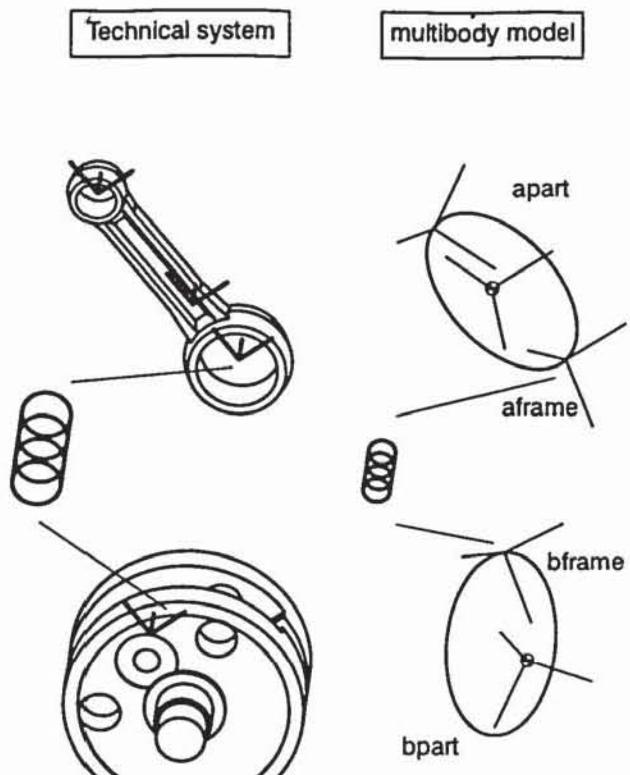




class: frame		
name	type	description
rframe	name	reference fr.
origin	dparam(3)	frame origin
axleseq	int(3)	rot. sequence
rangles	dparam(3)	rotation angles

object: frame1	
name	component
rframe	' '
origin	L1,L2,L3
	−44.21,0.0,0.0
axleseq	1,2,3
rangles	AL,BE,GA
	0.0,0.0,0.0

Fig 5 Definition of class *part*



class description		

class: interact		
name	class	description
connect	connect	frames to be connected
member	member	connecting element

class: connect		
name	class	description
apart	name	name of apart
aframe	name	name of aframe on apart
bpart	name	name of bpart
bframe	name	name of bframe on bpart

class: member		
name	class	description
joint	joint	joint element on interact
force	FORCE	force elements on i'act
sensor	SENSOR	sensor elements on i'act

Fig 6 Definition of class *interact*

$$r_i = [\ r_{i1}\ \ r_{i2}\ \ r_{i3}\ ]^T\ ,\quad i = 1(1)p, \tag{1}$$

of the centre of mass C_i and the 3x3−rotation tensor

$$S_i = S_i\ (\ \alpha_i\ \ \beta_i\ \ \gamma_i\ )^T\ , \tag{2}$$

written down for each body. The rotation tensor S_i depends on three angles α_i , β_i, γ_i and corresponds with the direction cosine matrix relating the inertial frame I and the body−fixed frame i to each other. The 3p translational coordinates and the 3p rotational coordinates (angles) can be summarized in a 6px1−position vector

$$x = [\ r_{11}\ r_{12}\ r_{13}\ r_{21}\ \cdots \alpha_p\ \beta_p\ \gamma_p\ ]^T\ . \tag{3}$$

Eqs. (1) and (2) read now

$$r_i = r_i(x),\quad S_i = S_i(x) \tag{4}$$

Secondly, the q holonomic, rheonomic constraints are added to the vehicle system given explicitly by

$$x = x(y, t), \tag{5}$$

where the fx1−position vector

$$y = [\ y_1\ \ y_2\ \ y_3\ \ \cdots\ \ y_f\ ]^T \tag{6}$$

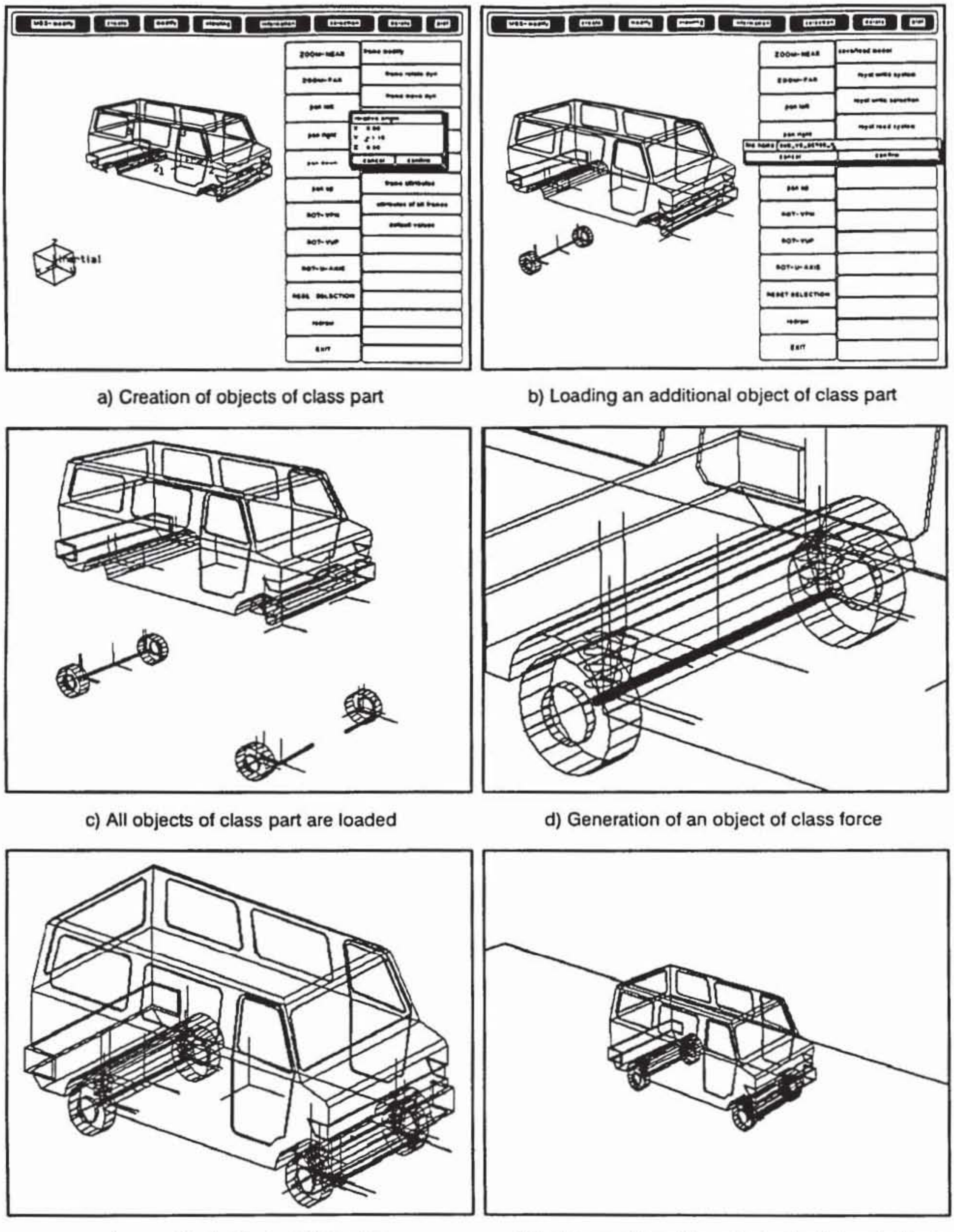
is used summarizing the f generalized coordinates of the system. The number of generalized coordinates corresponds to the number of degrees of freedom, $f = 6p-q$, with respect to the systems position. Then, translation and rotation of each body follow from (4) and (5) as

$$r_i = r_i(y, t),\quad S_i = S_i(y, t) \tag{7}$$

and the velocities are found by differentiation with respect to the inertial frame:

$$v_i = \dot{r}_i = \frac{\partial r_i}{\partial y}\ \dot{y} + \frac{\partial r_i}{\partial t} = J_{Ti}(y, t)\ \dot{y} + \bar{v}_i(y, t)\ , \tag{8}$$

$$\omega_i = \dot{s}_i = \frac{\partial s_i}{\partial y}\ \dot{y} + \frac{\partial s_i}{\partial t} = J_{Ri}(y, t)\ \dot{y} + \bar{\omega}_i(y, t)\ . \tag{9}$$



a) Creation of objects of class part

b) Loading an additional object of class part

c) All objects of class part are loaded

d) Generation of an object of class force

e) assembled object of class mbs

f) Exchange of graphic entity for inertial part object

Fig 7 Model assembly of a van

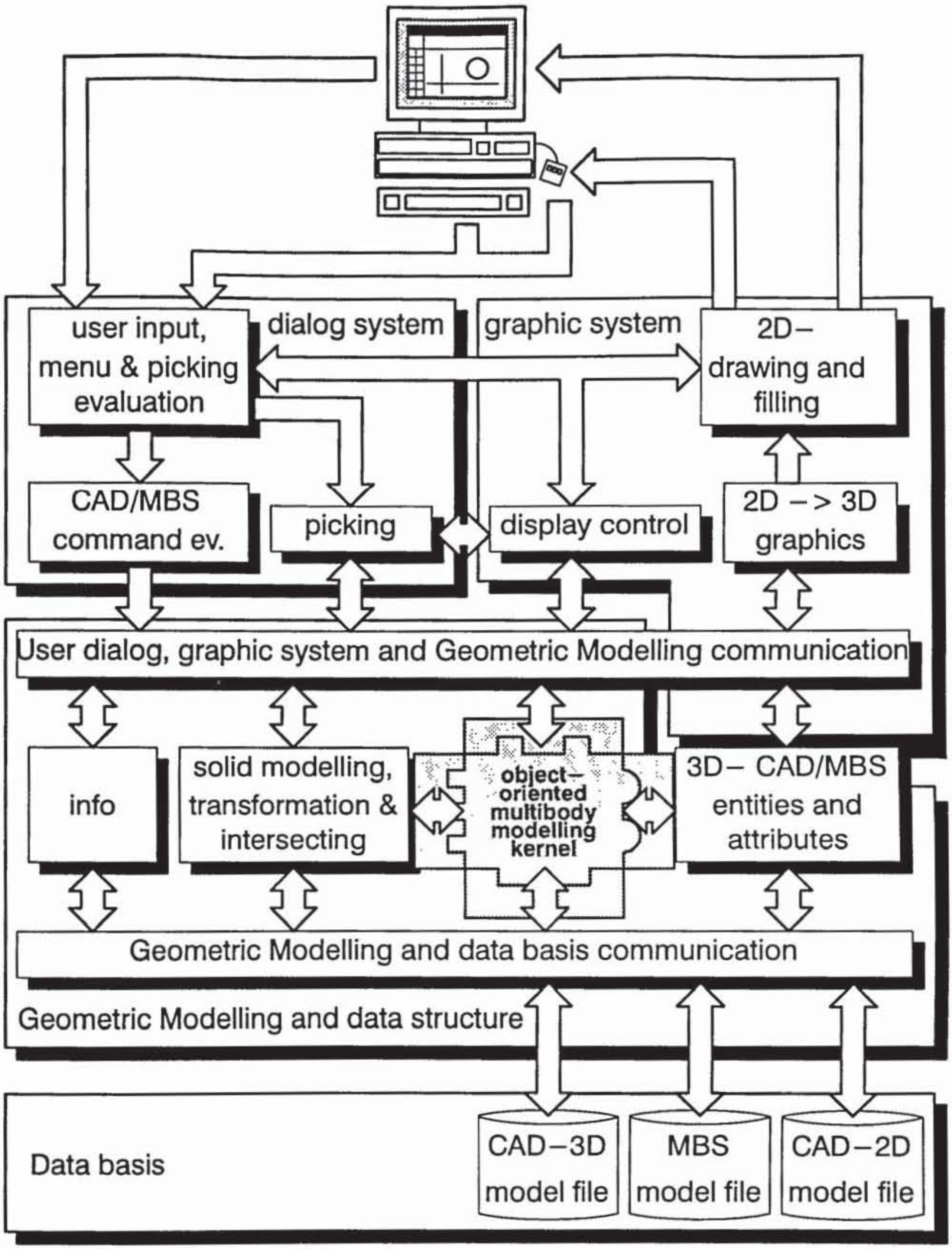


Fig 8 CAD software and multibody modelling kernel DAMOS-C

The 3xf−Jacobian matrices J_{Ti} and J_{Ri} defined by (8) and (9) characterize the virtual translational and rotational displacement of the system, respectively. They are also needed later for the application of d'A-lembert's principle. The infinitesimal 3x1−rotation vector s_i used in (9) follows analytically from the corresponding infinitesimal skew−symmetrical 3x3−rotation tensor. However, the matrix J_{Ri} can also be found by a geometrical analysis of the angular velocity vector ω_i with respect to the angles α_i , β_i , γ_i, see e.g. Ref. (13).

The accelerations are obtained by a second differentiation with respect to the inertial frame:

$$a_i = J_{Ti}(y,t)\ \ddot{y} + \frac{\partial v_i}{\partial y}\ \dot{y} + \frac{\partial v_i}{\partial t}, \quad (10)$$

$$\alpha_i = J_{Ri}(y,t)\ \ddot{y} + \frac{\partial \omega_i}{\partial y}\ \dot{y} + \frac{\partial \omega_i}{\partial t}. \quad (11)$$

For scleronomic constraints $x = x(y)$ the partial time−derivatives in (8), (9) and (10), (11) vanish. Vehicle models without rotating parts and position control devices are completely described by scleronomic constraints.

In many applications a reference frame is given in a natural way. For example, a railway vehicle running on a curved superelevated track is naturally described in a moving trackrelated frame. Therefore, the absolute motion may be also presented in a reference frame using the reference motion itself and the bodies' relative motion.

3.2 Newton−Euler Equations

For the application of Newton's and Euler's equation to multibody systems the free body diagram has to be used again. Now the rigid bearings and supports are replaced by adequate constraint forces and torques as discussed later in this section.

Newton's and Euler's equation read for each body in the inertial frame

$$m_i \dot{v}_i = f_i^e + f_i^r , \qquad i = 1(1)p, \quad (12)$$

$$I_i \dot{\omega}_i + \tilde{\omega}_i\ I_i\ \omega_i = l_i^e + l_i^r , \qquad i = 1(1)p. \quad (13)$$

The inertia is represented by the mass m_i and the 3x3−inertia tensor I_i with respect to the centre of mass C_i of each body. The external forces and torques in (12) and (13) are composed by the 3x1−applied force vector f_i^e and torque vector l_i^e due to springs, dampers, actuators, weight etc. and by the 3x1−constraint force vector f_i^r and torque vector l_i^r . All torques are related to the mass centre C_i . The applied forces and torques, respectively, depend on the motion by different laws and they may be coupled to the constraint forces and torques in the case of friction.

The constraint forces and torques originate from the reactions in joints, bearings, supports or wheels. They can be reduced by distribution matrices to the generalized constraint forces. The number of the generalized constraint forces is equal to the total number of constraints q in the system. Introducing the qx1−vector of generalized constraint forces

$$g = [\ g_1\ \ g_2\ \ g_3\ \ \cdots\ \ g_q\ ]^T \quad (14)$$

and the 3xq−distribution matrices

$$F_i = F_i(y,t), \qquad L_i = L_i(y,t) \quad (15)$$

it turns out

$$f_i^r = F_i\ g, \quad l_i^r = L_i\ g, \quad i = 1(1)p, \quad (16)$$

for each body. The constraint forces or the distribution matrices, respectively, can be found mathematically or they are derived by geometrical analysis.

The ideal applied forces and torques depend only on the kinematical variables of the system; they are independent of the constraint forces. Ideal applied forces are due to the elements of multibody systems, and further actions on the system, e.g. gravity. The forces may be characterized by proportional, differential and/or integral behaviour.

The Newton−Euler equations of the complete system are summarized in matrix notation by the following vectors and matrices. The inertia properties are written in the 6px6p−diagonal matrix

$$\overline{M} = \text{diag}\{\ m_1 E \quad m_2 E\ \cdots\ I_1\ \cdots\ I_p\ \}, \quad (17)$$

where the 3x3−identity matrix E is used. The 6px1−force vectors $\overline{q}^c$, $\overline{q}^e$, $\overline{q}^r$ representing the Coriolis forces, the ideal applied forces and the constraint forces, respectively, are given by the following scheme,

$$\overline{q} = \left[\ f^T_1\ \ f^T_2\ \ \cdots\ \ l^T_1\ \ \cdots\ \ l^T_p\right]^T . \quad (18)$$

Further the 6pxf−matrix $\overline{J}$ as well as the 6pxq−distribution matrix $\overline{Q}$ are introduced as global matrices, e.g.

$$\overline{J} = \left[\ J_{T1}{}^T\ \ J_{T2}{}^T\ \ \cdots\ \ \overline{J}_{R1}{}^T\ \ \cdots\ \ \overline{J}_{Rp}{}^T\right]^T . \quad (19)$$

Now, the Newton−Euler equations can be represented as follows for holonomic systems in the inertial frame

$$\overline{\mathbf{M}}\,\overline{\mathbf{J}}\,\ddot{y} + \overline{q}^c(y,\dot{y},t) = \overline{q}^e(y,\dot{y},t) + \overline{\mathbf{Q}}\,g\,. \qquad (20)$$

3.3 Equations of Motion

The Newton–Euler equations are combined algebraical and differential equations and the question arises if they can be separated for solution into purely algebraical and differential equations. There is a positive answer given by the dynamical principles. In a first step, the system's motion can be found by integration of the separated differential equations and in a second step the constraint forces are calculated algebraically. For ideal applied forces both steps can be executed successively while contact forces require simultaneous execution. Ideal applied forces depend only on generalized coordinates and their derivatives while nonlinear applied forces are depending on generalized constraint forces, too.

Holonomic systems with proportional or proportional–differential forces result in *ordinary* multibody systems. The equations of motion follow from the Newton–Euler equations, applying d'Alembert's principle.

The equations of motion of holonomic systems are found according to d'Alembert's principle by premultiplication of (20) with $\overline{\mathbf{J}}^T$ as

$$\mathbf{M}(y,t)\;\ddot{y} + \mathbf{k}(y,\dot{y},t) = \mathbf{q}(y,\dot{y},t)\,. \qquad (21)$$

Here, the number of equations is reduced from 6p to f, the fxf–inertia matrix $\mathbf{M}(y,t)$ is completely symmetrized $\mathbf{M}(y,t) = \overline{\mathbf{J}}^T\,\overline{\mathbf{M}}\,\overline{\mathbf{J}} > 0$, and the constraint forces and torques are eliminated. The remaining fx1–vector $\mathbf{k}$ describes the generalized Coriolis forces and the fx1–vector $\mathbf{q}$ includes the generalized applied forces.

In addition to the mechanical representation (21) of a multibody system, there exists also the possibility to use the more general representation of dynamical systems, e.g.

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u},t,\mathbf{p}), \qquad \mathbf{v} = \mathbf{g}(\mathbf{x},\mathbf{u},t,\mathbf{p})\,, \qquad (22)$$

where $\mathbf{x}$ means in (22) the state vector, $\mathbf{v}$ the output vector, $\mathbf{u}$ the input vector of controls, t the time and $\mathbf{p}$ the vector of mechanical and control parameters or design variables, respectively.

3.4 Formalism NEWEUL

The equations of motion presented are automatically generated by the formalism NEWEUL described in the Multibody Systems Handbook (12), too.

NEWEUL is a software package for the dynamic analysis of mechanical systems with the multibody system method. It comprises the computation of the symbolic equations of motion by the module NEWEUL and the simulation of the dynamic behaviour by the module NEWSIM.

Multibody systems are mechanical models consisting of

- rigid bodies,
- arbitrary constraining elements (joints, position control elements),
- passive coupling elements (springs, dampers), and
- active coupling elements (force control elements).

The topological structure of the models is arbitrary, thus possible configurations are

- systems with chain structure,
- systems with tree structure, and
- systems with closed kinematical loops.

The scleronomic or rheonomic constraints may be

- holonomic or
- nonholonomic.

The software package NEWEUL has been successfully applied in industrial and academic research institutions since 1979. The major fields of application are

- vehicle dynamics,
- dynamics of machinery,
- robot dynamics,
- biomechanics,
- satellite dynamics,
- dynamics of mechanisms.

The software package NEWEUL offers two approaches for multibody system modelling. These are

- the successive assembly approach using the kinematics of relative motions, and
- the modular assembly approach based on subsystems.

The input data for NEWEUL have to be entered in input files prepared with prompts and comments.

4 NUMERICAL SIMULATION OF AUTOMOTIVE SYSTEMS

NEWEUL generates the equation of motion of multibody systems in symbolic form. The computation is based on the Newton–Euler approach with application of the principle of d'Alembert for holonomic systems, and the principle of Jourdain for nonholonomic systems. The resulting equations of motion may be

- linear,
- partially linearized, or
- nonlinear

symbolic differential equations. Constant parameters can be included in numerical form. Nonlinear coupling elements in kinematically linear models are also permitted.

For the output format of the equations of motion several options are possible. FORTRAN compatible output allows the equations to be included in commercial software packages for dynamic analysis and simulation such as, for instance, ACSL. Another output format allows the processing of the equations with the formula manipulation program MAPLE.

Control parameters for compression and factorization enable the user to change the structure of the output equations, Figure 9. For example, the user may want to obtain fully symbolic equations of motion in order to check the results for modelling and input errors. Later, computationally efficient compressed equations can be generated for the verified model. Compression means that NEWEUL generates automatically abbreviations of symbolic expressions.

Fully Symbolic Output:

```
c>     Inertia Matrix
        M(1,1)=M1*A**2+I1
       +        M2*C**2+M3*C**2

        M(2,1)=-M2*B*C*SIN(AL1)*COS*(AL2)+
       +        M2*B*C*SIN(AL2)*COS*(AL1)
        M(2,2)=M2*B**I2

        M(3,1)=M3*B*C*SIN(AL1)*COS(AL3)-
       -        M3*B*C*SIN(AL3)*COS(AL1)
        M(3,2)=0.
        M(3,3)=M3*B**2+I3
```

Factorized Output:

```
c>      Inertia Matrix
        M(1,1)=(C*C*(M2+M3)+
       +        M1*A**2+I1))

        M(2,1)=C*B*M2*SIN(AL2-AL1)
        M(2,2)=(M2*B**2+I2)

        M(3,1)=C*B*M3*SIN(AL1-AL3)
        M(3,2)=0.
        M(3,3)=(M3*B**2+I3)
```

Fig 9 NEWEUL output of fully symbolic and factorized inertia matrix

The software module NEWSIM allows the simulation of the symbolic equations of motion provided by module NEWEUL. It automatically generates a problem specific simulation program. The user simply has to add the specification of

- force laws,
- system parameter values, and
- initial conditions.

The simulation results are stored in ASCII data files that can be visualized with arbitrary graphics packages. The software structure is shown in Figure 10.

The simulation results may contain

- the time history of the state variables,
- the kinematical data of observation points,
- data for animation,
- the time history of the reaction forces, and
- user-defined output data.

Apart from time simulations additional analyses can be performed with the module NEWSIM. These additional features include

- the quasi static analysis,
- the computation of the state of equilibrium and
- the treatment of the inverse dynamics problem.

The software package NEWEUL is written in FORTRAN 77 and can be implemented on any workstation or mainframe with a FORTRAN 77 compiler. NEWEUL uses its own formula manipulator.

5 COMPUTER AIDED VEHICLE ENGINEERING

The data model of multibody systems and the symbolical generation of equations of motion represent a strong basis for the analysis of vehicle dynamics problems. However, the vehicle is required to show some optimal behaviour, e.g. the data of the system have to be chosen properly. For this purpose optimization methods have to be applied and adjusted to vehicle dynamics problems, see BESTLE, EBERHARD and SCHIEHLEN (17).

Any of the data used for defining the multibody system can be chosen as design variables. The partial derivatives with respect to the design variables and the state variables required for the gradients in optimization methods may be computed symbolically by the programmable formula manipulation package MAPLE (18), too. The resulting equations of motion and the adjoint differential equations of the optimization are then solved by numerical integration. Because of the complexity of these equations and the dependence of the adjoint equations on state variables it is advantageous to use multistep integration algorithms and a corresponding interpolation scheme.

As an example the planar model of a van is presented, Figure 11. It consists of 4 rigid bodies, front and rear suspension including an active force control, and elastic tires. The 6x1-vector y summarizing the generalized coordinates reads as

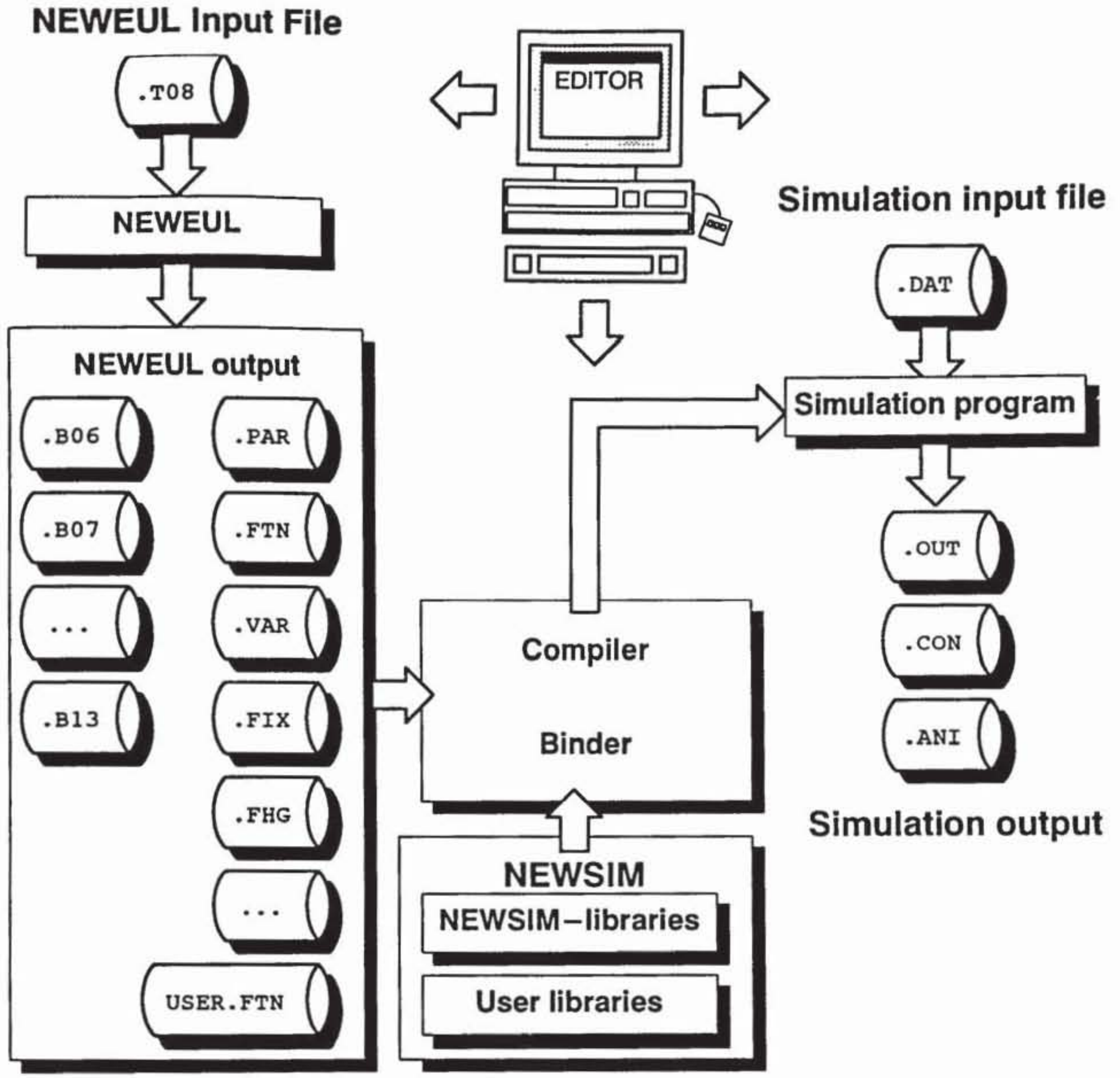


Fig 10 Software structure of NEWEUL

$$\mathbf{y} = [\ y,\ z,\ \alpha,\ \phi,\ w,\ z_S]^T . \tag{23}$$

The dynamic behaviour is described by a set of twelve first order differential equations of motion. The van is assumed to drive with a constant velocity of 20 m/s over a sinusoidal bump of height 0.1m and length 3m, often found in residential areas as 'sleeping policemen'.

The damping and stiffness coefficients of the front and rear suspension, i.e. d_F , d_R , c_F , c_R , the height of the centre of mass h_3, and in case of active suspensions the control parameter d_A are chosen as design variables. They can be summarized in the 6x1–vector of design variables

$$\mathbf{p} = [\ d_F\ ,\ d_R\ ,\ c_F\ ,\ c_R\ ,\ h_3,\ d_A\ ]^T . \tag{24}$$

Optimization of the vehicle has been performed using the multicriterion ψ of driving comfort ψ_C, driving safety ψ_S, and relative suspension displacement ψ_D,

$$\psi = w_C \frac{\psi_C}{\psi_C^*} + w_S \frac{\psi_S}{\psi_S^*} + w_D \frac{\psi_D}{\psi_D^*} ,$$

$$\psi_C = \int_{t^0}^{t^1} t^2 \ddot{z}_S^2 \, dt ,$$

$$\psi_S = \int_{t^0}^{t^1} (z_Q - z_R)^2 \, dt ,$$

$$\psi_D = \int_{t^0}^{t^1} \left(\frac{z_P - z_Q}{s_0} \right)^6 dt . \tag{25}$$

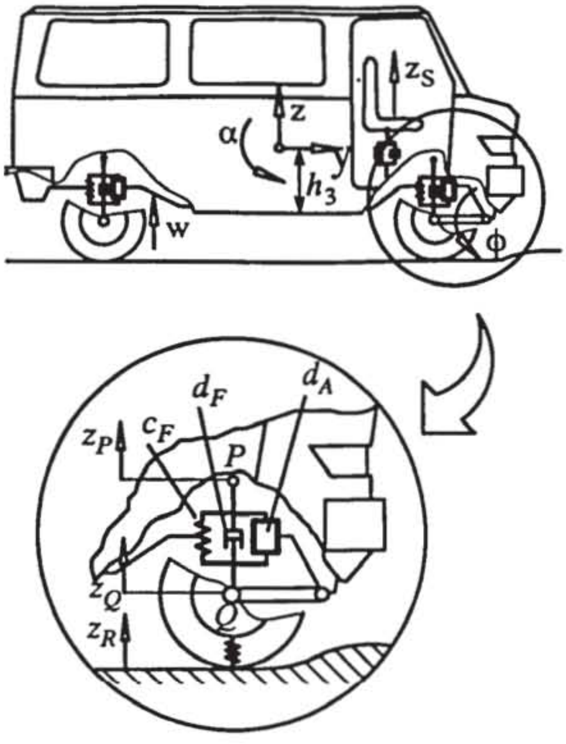


Fig 11 Planar model of a van

The weighting factors in (25) are normalized to $w_C + w_S + w_D = 1$ by the single criteria $\psi(1/0/0) = \psi_C^*$, $\psi(0/1/0) = \psi_S^*$, $\psi(0/0/1) = \psi_D^*$.

Figure 12 shows the riding comfort of an optimized design using single criteria. Considering the relative displacement leads to high maximal accelerations while optimization of the riding safety yields low but poorly damped accelerations. The analysis of conflicting optimization criteria shows that the improvement of one criterion worsens the other criteria. Thus, only a multicriteria approach will give an engineering trade–off. E.g., if a multicriterion is used instead of the comfort criterion ψ_c^* only, the improvement in riding comfort is not as high. However, the final result shows a strong improvement of the riding comfort compared to the initial situation without much cost in riding safety or relative displacement. It will be a matter of engineering intuition to make a good choice on the weighting coefficients w_c, w_s, w_d.

6 CONCLUSION

A simulation based design of automotive systems requires modelling by well defined multibody system datamodels. The object–oriented approach of modern software engineering is most adequate for multibody system data management. Formalisms generating symbolic equations of motion are efficient for dynamical analysis, simulation and optimization of vehicle systems. Advanced vehicle design has to consider quite a number of performance criteria and requirements. Software engineering concepts are most important to dynamical vehicle analysis within the overall design procedure.

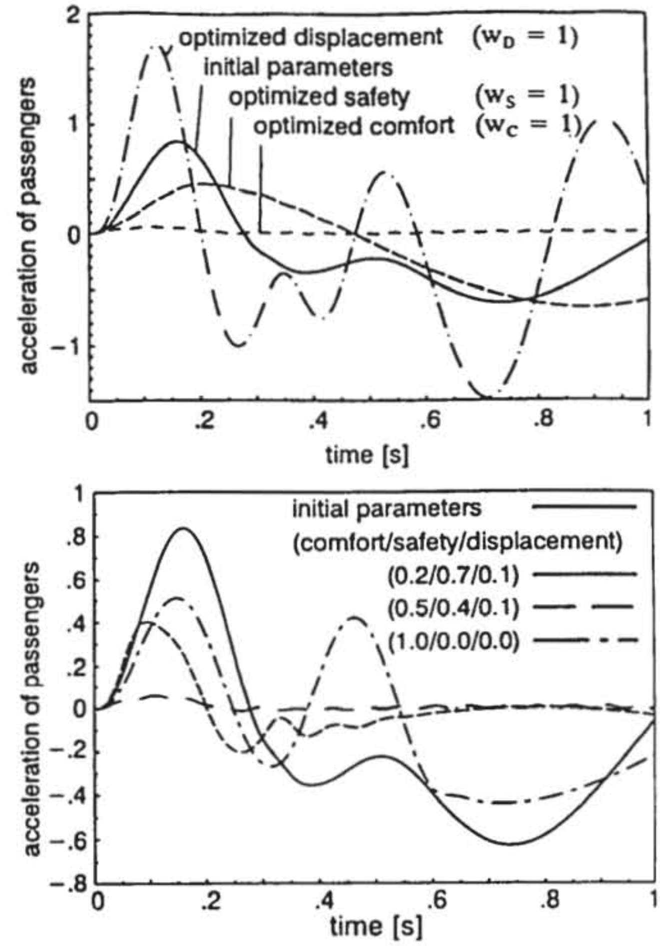


Fig 12 Single and multicriteria optimization

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