DELFT-TYRE
a design and analysis tool for modelling and simulation of tyre behaviour

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Contents

Abstract

TNO is developing the design and analysis toolbox DELFT-TYRE in cooperation with the Delft University of Technology. This toolbox supports testing and modelling of tyre behaviour and is based on the Magic Formula tyre model.

It can be used with any dynamic system simulation code and consists of four different modules:

- **MF-TOOL** the central graphical user interface, manipulation of tyre characteristics;
- **MF-TYRE** a subroutine for simulation of tyre behaviour;
- **MF-FIT** for calculation of Magic Formula parameters out of measurement data;
- **MF-DATABASE** a tyre property database.

1 Introduction

The combination of road, tyre, vehicle and driver forms one entity. The mechanical characteristics of the tyre in contact with the road must combine with the mechanics of the vehicle to help producing operational characteristics of the tyre-vehicle system which are satisfactory to the driver.
Tyres determine to a great extent the dynamic behaviour of road vehicles. The major disturbances and the control forces on a vehicle arise from the contact between tyres and road. Vertically, the weight of the vehicle is transferred to the road by the tyres. The compliance of the tyres cushions a vehicle against disturbances due to small road irregularities. The forces required for traction and braking arise from the longitudinal tyre forces. Lateral tyre forces are required for controlling the direction of travel of the vehicle. The lateral behaviour of tyres are dominant factors for vehicle stability.
The tyre-road contact forces depend on the characteristics of the tyre (the stiffness and damping), the road condition (the friction coefficient between tyre and road), and the motion of the tyre relative to the road (the amount of slip).
The analysis of the influence of tyre properties on the dynamic behaviour of vehicles requires an adequate model of the tyre-road contact phenomenon. The Magic Formula tyre model [1, 2, 3] provides a set of mathematical formulae from which the forces and moments acting from the road to the tyre can be calculated at pure and combined slip conditions. The Magic Formula model aims at an accurate description of the measured steady state behaviour of a tyre. Since 1987 this empirical tyre model, which is partly based on physical insight into the tyre force generating properties, has been developed and improved in a cooperative effort of the Delft University of Technology and Volvo. At this moment the development is continued by the Delft Vehicle dynamics Research centre (DVR), which is a cooperation of the TNO Road-Vehicles Research Institute and the Vehicle Dynamics Laboratory of the Delft University of Technology.
A global overview of the DELFT-TYRE product line is given in section 2 of the paper. The functions of the different modules are explained. Section 3 will emphasize on MF-TYRE as a module of DELFT-TYRE and its relation to the other modules.

2 The DELFT-TYRE product range

2.1 Introduction

In order to provide the engineer with a complete tool with which he can simulate tyre behaviour, the product range DELFT-TYRE has been developed. DELFT-TYRE is a design and analysis toolbox which supports testing and modelling of tyre behaviour. It can be used with any dynamic system simulation code and consists of four different modules (each starting with the acronym 'MF' which is an abbreviation of Magic Formula), see also figure 1.
All tools run under UNIX on a work station. Except for MF-TYRE, the DELFT-TYRE modules will be introduced at the end of 1995 and will be supplied directly by DVR.

2.2 Different softeware modules in DELFT-TYRE

2.2.1 MF-TYRE

MF-TYRE is a subroutine for modelling and simulation of tyre behaviour. Its equations are based on the latest (1995) Magic Formula tyre model [3]. MF-TYRE describes both pure and combined slip, using longitudinal and lateral slip quantities κ and α, wheel camber γ and wheel load F_z as input. The model takes into account plysteer and conicity. In the 1995 version of MF-TYRE, non-steady state behaviour is included in the model by differential equations describing lag for both longitudinal and lateral tyre slip. The subroutine is intended to be used in cooperation with a wide range of simulation codes. The interface between simulation codes and MF-TYRE will be conformed to the Standard Tyre Interface (STI), defined in the Tyre Workshops.

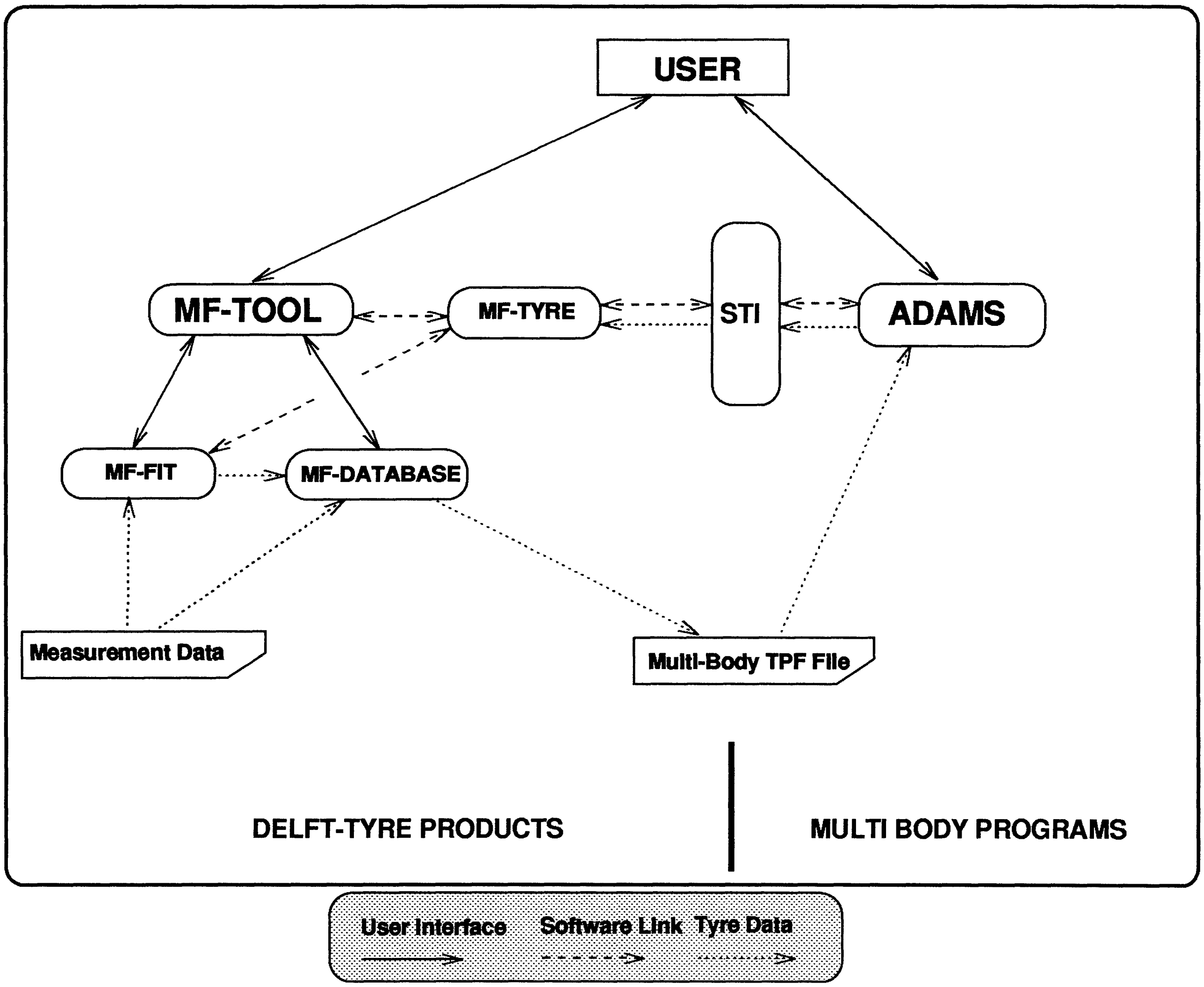

Figure 1: DELFT-TYRE components and internal/external relations

The MF-TYRE module of DELFT-TYRE will be commercially available in the summer of 1995. It will be distributed through suppliers of commercially available multi-body software. In ADAMS, MF-TYRE will be distributed 'on the tape' and made available to users by using a password protection. First help and support will be supplied by local ADAMS representatives. In depth support for tyre related problems will be the responsibility of DVR.

2.2.2 MF-TOOL

MF-TOOL is the central graphical user interface (GUI) of DELFT-TYREIt is used for interaction to MF-FIT and MF-DATABASE, for visualisation of tyre characteristics and preparation of user defined datasets. It offers the possibility to visually manipulate tyre characteristics through alteration of Magic Formula tyre coefficients (see figure 2). This way, users can define their own tyre characteristics and use them for simulation purposes. Through variation of the coefficients, the effect of tyre behaviour on the dynamics of the complete vehicle becomes clear. Tuning of tyre characteristics will optimize vehicle dynamics in the long run.
Communication between MF-TOOL and multi-body programs is performed through the use of Tyre Property Files (TPF-file). TPF-files for a certain multi-body program are created by MF-TOOL on user request. Data for a certain tyre is extracted from MF-DATABASE and written to an ASCII file with the format defined by the multi-body program.

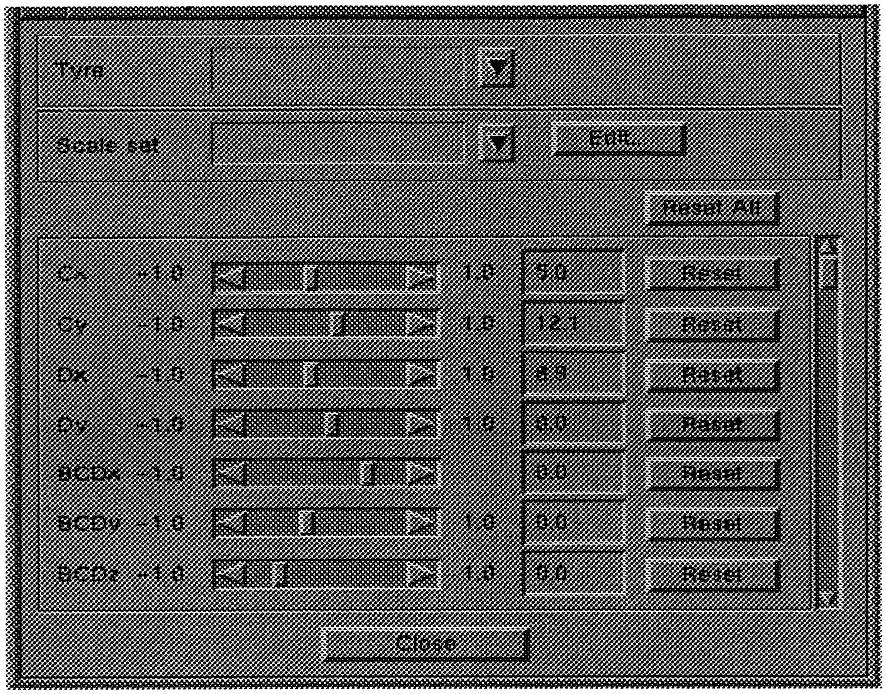

Figure 2: MF-TOOL dialogue for variation of MF coefficients

2.2.3 MF-FIT

Calculation of the Magic Formula parameters out of measurement data is done with the module MF-FIT. MF-FIT uses the latest Magic Formula version.
After the first processing of the "raw" measurement results, a regression method determines the parameters from the data. In the current version of MF-FIT, fitting is performed in a stepwise manner. Parameters determined by the pure slip condition measurements form the basis for the fitting of combined slip measurement data. In the near future MF-FIT will contain automatic generation of starting values.
The input of tyre data in MF-FIT will agree with the TYDEX (Tyre Data Exchange) format. This format is a result of discussions between experts in the field of tyre manufacturing, measurements and users of mathematical tyre models in the Tyre Workshops. Representatives of TNO and the Delft University of Technology are two of the initiators of the Workshops.
MF-FIT will be made available as a stand-alone batch program and can be accessed using MF-TOOL. Using MF-TOOL, graphical feedback of fitting progress and results will be presented on-line. Figure 3 shows a prototype of a form in the fitting part of MF-TOOL.

2.2.4 MF-DATABASE

MF-DATABASE is a user friendly database for storing information of tyre characteristics. In addition, tyre property values and measurement characteristics can be added to specific tyre information. The user will get access to the database through MF-TOOL. Users of MF-DATABASE will receive regular new datasets when this is included in the contract.

2.2.5 DELFT-TYRE Test Trailer

In support of the DELFT-TYRE software product range, the DELFT-TYRE Test Trailer can measure characteristics of passenger car and motorcycle tyres under combined slip conditions. Data measured by the Test Trailer can be ordered in a DELFT-TYRE contract. Measurement results will be presented to the customers in tyre data sets, possibly stored as a part of MF-DATABASE.

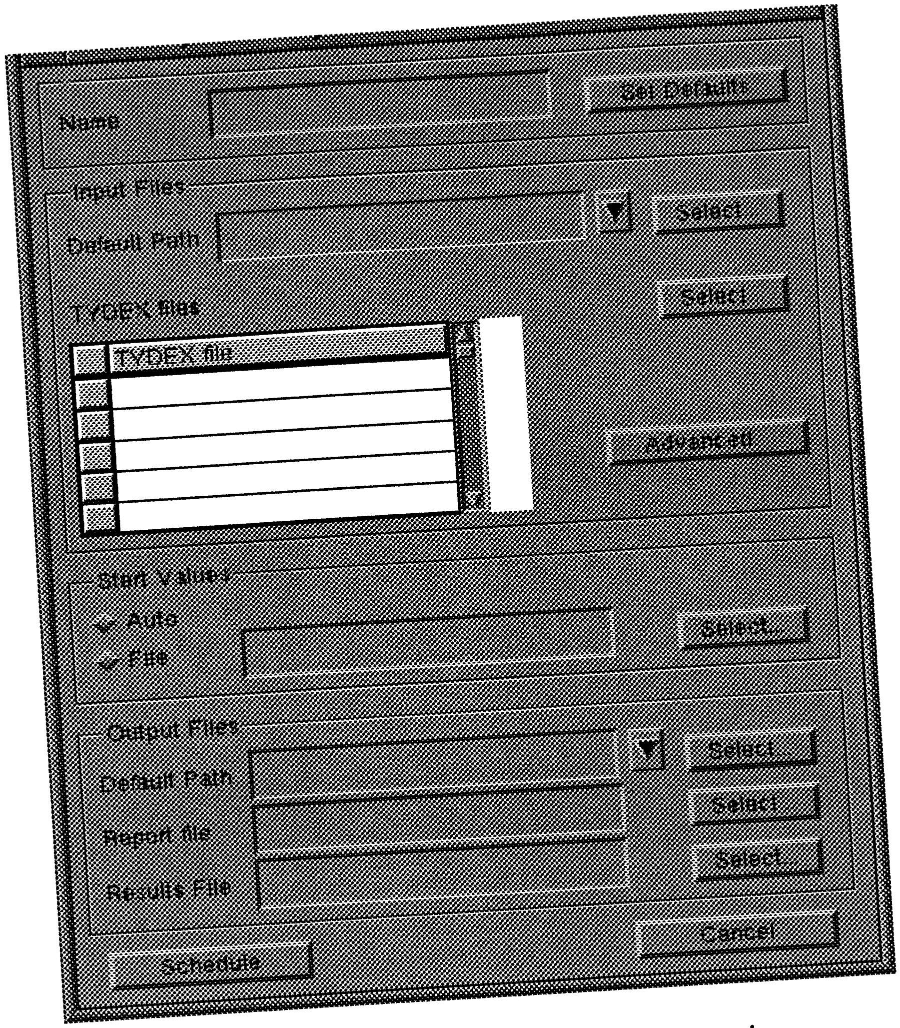

Figure 3: MF-TOOL dialogue for entering fit options

3 Detailed Description of MF-TYRE

The MF-TYRE software is separated in a steady state part and a dynamic part. Until recently, the latter of the two has been used mainly as an 'add-on' to the steady state version. In the 1995 version of MF-TYRE, a more complete description of dynamic tyre behaviour is implemented. This results in a more modular and better combined approach of representing tyre equations.

For a number of reasons, this paper will not list the full set of tyre equations used in MF-TYRE. One of the reasons is that currently, parts of the software are still in testing phase. The main reason however is that Professor Pacejka himself will publish the complete description of the formulae in the second part of this year. The paper presented here will put more emphasis on implementation aspects of MF-TYRE.

3.1 Steady state tyre behaviour

For the 1995 version of DELFT-TYRE, the Magic Formula has been modified significantly. Main purpose of the modifications was to obtain better maintainable tyre equations with a wider range of application. The most significant modifications will be discussed here.

3.1.1 Dimensionless equations

All Magic Formula tyre parameters are made dimensionless using a tyre specific force and geometry quantity. All wheel load dependencies are rewritten to polynomials with the origin of the independent variable at the nominal load of the wheel. Dimensionless parameters for the torque equations are obtained using the free radius of the tyre.
This results in a set of equations with a number of strong features:

- All tyre parameters are dimensionless and will be in a smaller band around the unit value. As a consequence, fitting of measurement data will give less numerical problems and will not require further internal scaling of data, a process that was sometimes used in older fitting software.
- Tyre parameters will be more independent of tyre geometry and use. This means that differences between tyres for passenger cars and tyres for trucks will be smaller. Another consequence of this is that starting values of parameters for the fitting process can be used in a wider range of tyres.

3.1.2 Naming of MF-parameters

The naming convention of all Magic Formula parameters used has been revised. This results in better readable MF-equations and more support towards future model extensions.
Both in papers and in software, names of all MF-parameters are defined as:
a_{ijk}
Where

- $a = p, q, r$, or s
  denotes whether a parameter is used for pure/combined force/torque;
- $i = B, C, D, E, K, H, V$, or T
  denotes for which of the Magic Formula coefficients this parameter is used;
- $j = x, y$ or z
  denotes the direction of the force or torque;
- $k = 1, 2, .., 9$,
  is used for a further indexation of the parameter.

3.1.3 Scaling factors

A total of 24 scaling factors is introduced in the tyre equations. These scaling factors are set to unit value during the fitting process and can be modified by users to adjust all characteristics of a tyre. Scaling factors are defined for pure slip behaviour such as rated load, peak friction and stiffness coefficients as well as for camber effects and tyre shifts. Also tyre trail and residual torque effect can be scaled. Combined slip and transient tyre response can be influenced using 7 scaling factors.
Using scaling factors, a number of existing problems can be solved more efficient:

- building a library of tyre models with small but prescribed relative differences can be done simply by copying tyre data files and modification of one single tyre scaling factor;
- tyre parameter variations for model optimisation or sensitivity analysis can easy be implemented;
- specification of desired tyre behaviour to tyre manufacturers is supported;
- modelling of transient behaviour such as variation of the friction coefficient as a function of time or wheel location can be done by variation of one single tyre parameter.

3.1.4 Pure slip and combined slip

The software describes both pure slip and combined slip torques and forces and takes into account the effect of tyre camber. The aligning torque equations are based on recent developments from Michelin engineers. In this method, aligning torque is calculated using a magic formula based calculation of the pneumatic trail. In the resulting aligning torque relations, a residual torque is introduced to describe remaining tyre effects.

3.2 Modelling of tyre dynamics

In the 1995 version of MF-TYRE, tyre dynamics is modelled both in longitudinal and in lateral direction. First order lag equations are defined for tyre longitudinal deformation u and tyre lateral deformation v. These deformations are used to define dynamic slip quantities κ' and α' that replace κ and α in the steady state tyre equations. One interesting consequence of the current equations is an improved ability to model low speed tyre behaviour.
The lag equations mentioned introduce tyre relaxation length for longitudinal and lateral tyre behaviour. For reasons of numerical stability and independence of the applied numerical integration method, differential equations are defined to describe the relaxation lengths.
The gyroscopic couple in the tyre contact is taken into consideration using the time derivative of the lateral tyre deflection. As was already mentioned, a scaling parameter has been defined to introduce scaling of the effect of gyroscopic couple in dynamic tyre behaviour.

3.3 Implementation aspects of MF-TYRE

MF-TYRE is basically defined as one single Fortran 77 subroutine. The module describes the behaviour of tyre-road contact. In all DELFT-TYRE software a single contact point between tyre and road is considered.
Input variables for this subroutine are:

1. **simulation model states** MF-TYRE takes a number of contact point variables to calculate tyre contact forces and torques. The most relevant variables used are:
   - vertical load at the wheel in Newtons;
   - longitudinal and lateral slip in units and radians respectively;
   - camber angle in radians.
2. **tyre parameters** All Magic Formula parameters are introduced using a one dimensional array. The array is passed by the calling program in the argument list of the subroutine. Using this construction, unlimited access to tyre parameters from the multi-body environment is guaranteed. Besides all MF-parameters, a number of extra parameters are stored:
   - allowed ranges of simulation input variables to check validity of calculation results;
   - radial stiffness, radial damping and tyre nominal load for description of vertical tyre behaviour;
   - scaling parameters to scale tyre characteristics;
   - geometrical parameters for visualisation of the tyre by the simulation program;
   - switches for tyre identification and for skipping parts of the tyre behaviour. Using the latter, faster simulations can be obtained in simplified simulation runs (lateral tyre behaviour only).

Output variables of MF-TYRE are the three components of tyre contact force and torque stored in one single array.

3.4 Use of MF-TYRE in other software

MF-TYRE represents the contact force generating module and is used in the other software modules in DELFT-TYRE. Its use is slightly different for each of the modules.

3.4.1 MF-TYRE in MF-FIT

MF-TYRE is used in MF-FIT to generate the error function required by the parameter optimisation software. For each point in the measured force and torque signals, MF-TYRE calculates a value using the current MF-parameters. Using the error between measured and calculated data, the fitting software will continue varying MF-parameters until all measurement points are represented with a minimised error.

3.4.2 MF-TYRE in MF-TOOL

MF-TOOL uses MF-TYRE to generate tyre forces and torques for a given set of MF-parameters and for a given range of input variables. This procedure is applied to generate force and torque characteristics. MF-TOOL enables users to perform on-line variation of scaling parameters and (if applicable) MF-parameters. The results of parameter variations are directly fed back to the user with an on-line visualisation of the curves. Thus, all direct and indirect consequences of a parameter variation can be assessed immediately and interactively.

3.4.3 MF-TYRE in multi-body programs

The first part of DELFT-TYRE to be marketed is MF-TYRE as part of a multi-body program. As multi-body programs are essentially outside of the DELFT-TYRE software, a special procedure is followed to input tyre parameters into MF-TYRE (see figure 1). Currently, no direct interface between MF-DATABASE and MF-TYRE exists. However, if future multi-body software will develop in this direction, the option will most certainly be considered in DELFT-TYRE. For present installations, all MF-parameters for a certain tyre are extracted from MF-DATABASE into a documented and readable ASCII Tyre Property File. These files will be read by the multi-body software in the starting phase of each simulation run. Using TPF files gives users much flexibility and agrees with current procedures in tyre data presentation. All other input variables of MF-TYRE are results of the simulation in the multi-body code and are passed to MF-TYRE through the argument list of the routine.

3.5 Development of MF-TYRE

In the development of DELFT-TYRE, much attention is focused to support development of new versions of MF-TYRE in all software modules. One of the consequences of this is that part of the central tyre database is reserved for definition of the characteristics of all MF-parameters in a version of MF-TYRE. Examples of stored characteristics of a certain MF version are:

- default value, 'not used' value, maximal and minimal value allowed for a parameter;
- an one-line description of the parameter, to be used in documentation and user interfaces;
- coding of the functionality of a parameter. This code is used by MF-FIT to decide whether parameters are fixed or varied while fitting certain measurement data.

4 Interaction MF-TYRE versus ADAMS

4.1 MF-TYRE in ADAMS using STI

Recently, the steady state version of MF-TYRE has been implemented in ADAMS 8.1. It will be made available to $\beta-$ site users upon request. In this installation, many aspects have been considered

to support future development of both ADAMS and DELFT-TYRE software components. The most relevant choice made in this respect was the use of the Standard Tyre Interface to perform communication between MF-TYRE and ADAMS. Intentionally, use of this interface will ensure that a wide range of simulation software can be linked to a wide range of tyre software available. The implementation of the STI interface in ADAMS has been completed successfully and resulted in a number of observations and suggestions towards the TYDEX group defining this interface. These remarks have been presented at the most recent meeting of the TYDEX group and are now being investigated.
The standard Tyre Interface prescribes a subroutine call with a number of subroutine arguments to pass all relevant information from tyre models to multi-body programs and vice versa. The subroutine represents a shell around tyre software and is fixed to the axle hub which is modelled by the multi-body programs. As MF-TYRE considers its interface at the contact patch, extra software is included to link the contact patch to the axle of the wheel. All angle transformations necessary from the frame of the axle to the frame of the road are included in this software.

4.2 STI versus ADAMS

The definition of the STI shows much resemblance to ADAMS/TIRE. Therefore the place to implement STI in ADAMS is inside ADAMS/TIRE. As a consequence, changes required for ADAMS users switching over from existing tyre models to DELFT-TYRE are limited to replacement of the *MODEL = XXXX* statement by *MODEL = DELFT*. A number of predefined anonymous Tyre Property Files are included in ADAMS for users that take the DELFT-TYRE option. In the 9.0 release of ADAMS, dynamic tyre behaviour as described in this paper will be implemented. No user changes will be required to switch to dynamic tyre behaviour as the format of Tyre Property Files is already defined to store parameters for dynamic behaviour.
Some interesting aspects in the user interface of MF-TYRE in ADAMS are:

- The ADAMS ROAD module is called to generate height and slope of the road at the contact point. As a result, no limitations exist in the use of road models with respect to other tyre models.
- The tyre software performs a number of error checks on correctness of tyre parameters and checks of tyre conditions during simulation runs. All error messages and warnings are passed from the STI to the ADAMS error reporting system. As a result, full compatibility is obtained to other error messages generated by ADAMS. This strongly supports debugging of mistakes in user input data and detection of undesired vehicle conditions during simulation runs.
- The complete list of variables calculated in the tyre model is passed to the ADAMS REQUEST list. Thus, full user access to tyre performance and calculations is offered during simulation runs. The complete list of tyre output variables is still a point of discussion in the STI definition. ADAMS users of DELFT-TYRE models are invited to report specific desired variables in the tyre output list.

4.3 MF-TYRE versus ADAMS CAR

Recent developments in ADAMS indicate increased interest in parameter optimisation and component modelling. Due to the use of dimensionless parameters and scaling values, DELFT-TYRE is fully adapted to these requirements.
However, for this to work properly, ADAMS must be able to consider tyres as a model component and must be able to modify tyre characteristics automatically. The major consequence is that, for a parameter optimisation to work adequately, the main program must know about the internal data in a tyre model. This however is in contradiction with demands placed on a *standardised* tyre interface.
In the installed version of MF-TYRE in ADAMS, the definition of the STI has been extended to allow passing of tyre properties (i.e. scaling values). This means that indexes of important tyre parameters are known both to the tyre model and to ADAMS. Although this process took a significant part of the

installation of MF-TYRE in ADAMS, the possibilities of the method with respect to developments in ADAMS such as ADAMS CAR are promising.
Other possible consequences of the method are that users can manipulate tyre characteristics directly from the model definition file. As an example, road friction variation can be described with model statements influencing the scaling factor of the tyres. Users do not have to make extra Fortran code modifications to obtain this parameter variation.

4.4 Implementation of dynamic tyre models

A number of extra complications arise when modelling tyre dynamics. Although a set of dynamic relations are already derived and tested in DELFT-TYRE, it has not yet been implemented in ADAMS. This decision is not taken lightly and is based on a number of considerations. The most important one is that, due to the amount of differential equations and their complexity, MF-TYRE is modelled more accurately and reliable with a *global* integration scheme.
In former tyre models, as in most of the existing tyre models in ADAMS, integration is performed either by:

1 application of differential equations to single component forces and/or torques;

2 a local integration scheme;

3 replacing differential equations with an approximation formula.

Each of the methods listed has a number of disadvantages:
Method 1):

- this method cannot be applied when combined slip characteristics are required;
- model definition files will be unnecessary complicated due to the extra statements required.

Method 2):

- Local integration schemes must keep track of the time in the central (or global) integration scheme. This may cause problems when using complicated (stiff) integration schemes such as typically used in the ADAMS set of differential equations.
- The dynamic tyre equations are not recognised as state variables to the main program. Therefore, eigenfrequency analysis of models using this method will not give reliable results. As an example, motorcycle vibration modes related to tyre slip can never be described adequately.
- Local integration doesn't supply a standard way for modification of initial conditions. Using global integration, this is done simply by modification of the global state vector.

For method 3):

- Using a replacement set of equations has all disadvantages of method 2).
- A further deterioration of the reliability of this method is expected with increasing complexity of dynamic tyre model equations.

Another strong feature gained when making a *clean* implementation of the dynamic tyre equations in MF-TYRE is that physically seen, the contact behaviour of a tyre at low speed switches over to a that of a spring. Consequently, initialisation of tyre models will no longer be a problem in ADAMS vehicle models.

4.5 Development scheme of MF-TYRE in ADAMS

For the reasons explained in this paper, the following development procedure for MF-TYRE has been agreed between MDI and DELFT-TYRE representatives.

1. The steady state version of MF-TYRE will be installed in ADAMS 8.1 using the STI with the extensions mentioned above. With this, most of the interface between MF-TYRE and ADAMS and its users has been specified. For the dynamic model, a number of unused arguments in the steady state version will be activated to pass dynamic tyre properties.

2. The dynamic version of MF-TYRE will be implemented in ADAMS 9.0 in the second part of 1995. Possible modifications following from user response to the steady state version will be considered for this release. For this implementation, DVR will assist MDI in adjusting the ADAMS/TIRE statement allowing it to define differential equations using the global integration scheme.

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