Linearisation of stiffness and damping characteristics of rubber bushes in vehicle dynamics by using frequency response analysis of MSC/NASTRAN.

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Abstract:

For vehicle dynamics analysis detailed modelling of bushes is necessary. The following paper describes different possibilities to use measurement data of rubber bushes by linearisation of stiffness and damping characteristics in frequency response analysis.

1 Introduction

Analyses in the field of driving comfort are of great importance today in the development of motor vehicles. Driving comfort is influenced decisively by all vibrations excited during the operation of the vehicle. The causes of these vibrations are imbalance, uneven road surfaces and engine shake. In the case of uneven road surfaces, for example, vibrations are transferred from the tires via the suspension, the body, seats and even the steering wheel to the driver.

MSC/NASTRAN is a recognised tool for analysing driving comfort and hence the calculation of driving dynamics. For this purpose MSC/NASTRAN offers the solution SOL111 "modal frequency response". This frequency response analysis describes the harmonic response of a system in steady state caused by harmonic and frequency-dependent excitation. In such case, the forces of excitation are of the same frequency but may have differing phase angles at various degrees of freedom.

The Solution 111 only takes into account geometric linearity. This is valid as long as the amplitudes remain small, which is the case in most driving situations. It is only under particular driving conditions such as on very uneven surfaces or for the analysis of the structure under abuse loading that geometric linearity is no longer guaranteed.

In a vehicle system analysis, material non-linear effects occur particularly in suspension bushes. This is because the dynamic stiffness of the bushes is a function of the amplitude of the vibrations which occur. These material non-linear effects can not be taken into account with MSC/MASTRAN SOL111. But those bushes with non-linear material behaviour are exactly the ones which have a significant effect on the results of the calculation of driving dynamics. That is why their exact representation is crucial to obtaining calculation results which closely reflect the reality.

The following are necessary in order to calculate a good vehicle dynamic response:

1. The dynamic stiffness of the bushes must be known
2. The material non-linear behaviour of the rubber bushes must be taken into account in a material linear calculation (MSC/NASTRAN SOL111)

The following solution is offered:

On servo-hydraulic test machines it is possible to measure the characteristics for non-linear stiffness and damping of each individual bush depending on preload, direction, frequency and amplitude. The non-linear material behaviour can then be taken into account by means of an iterative procedure by establishing the displacement of each bush in an initial calculation. In a second step the stiffness of the bush is updated according to amplitudes based on measurements and a new analysis is performed. This methodology is repeated until the stiffness of the bush ceases to change or until the change is only minimal.

Figure 1 shows the result of a frequency response analysis for a vehicle system model in the form of a frequency response at a point which affects driving comfort. Linearisation should result for the frequency at which maximum acceleration occurs.

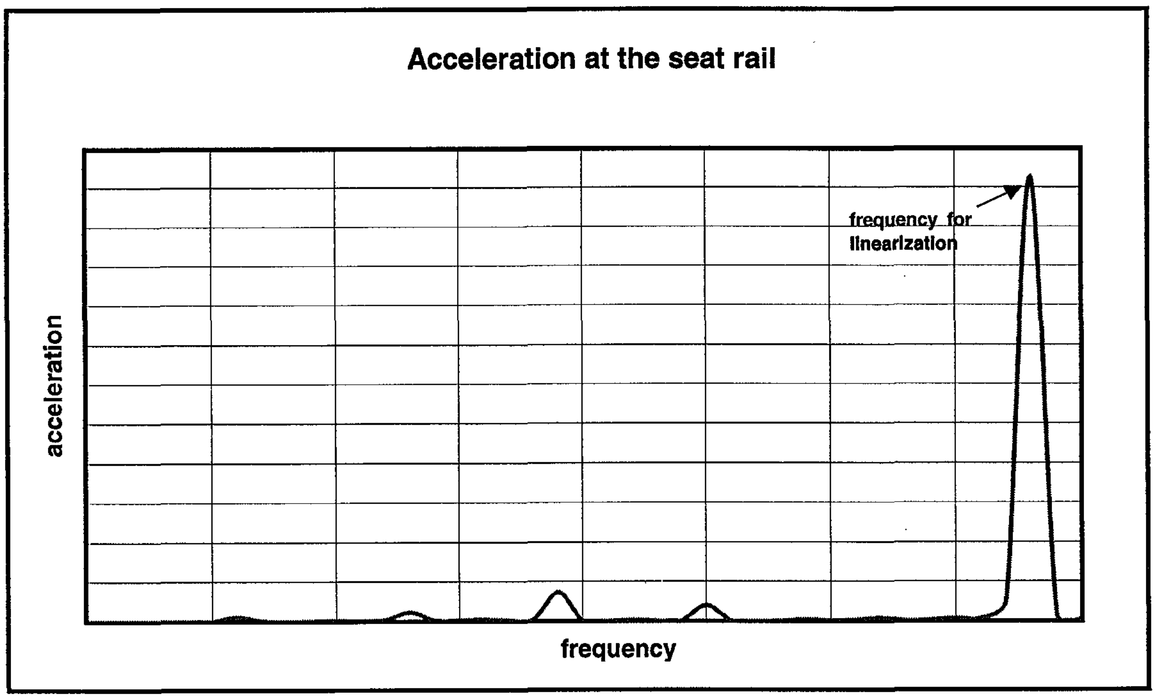


Figure 1

This iterative method of determining the dynamic stiffness of rubber bushes has been applied within the PELIT application by P+Z Engineering for AUDI AG and is explained in greater detail in this article.

2 Characteristics and modelling of bushes

2.1 Physical description of the rubber bushes

In regard to damping, a distinction is made between material damping and viscous damping.

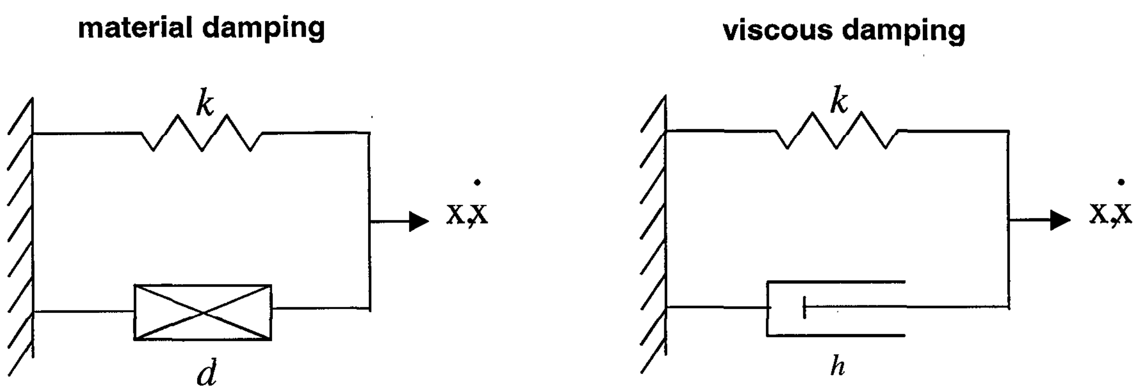


Figure 2: Material damping and viscous damping

The force-displacement relationship is:

$$F = (k + i \cdot d) \cdot x \qquad\qquad F = kx + h\dot{x}$$

With the displacement formulation

$$x = x_0 \cdot e^{i\omega t}$$

The force-displacement relationship is:

$$F = (k + i \cdot d) \cdot x_0 e^{i\omega t} \qquad\qquad F = (k + ih\omega) \cdot x_0 e^{i\omega t}$$

The result for the complex stiffness is therefore:

$$k_{komplex} = (k + i \cdot d) \qquad\qquad k_{komplex} = k + i\omega h$$

The dynamic stiffness is the magnitude of the complex stiffness.

Tests have shown that dynamic stiffness depends on the following factors:

- Preload on the bush under static load
- Excitation frequency
- Size of amplitude of the vibration

These factors are explained in greater detail below.

3 Factors affecting the dynamic stiffness of bushes in a Frequency Response Analysis

Preload

These are the forces acting on the bush which result from the weight of the vehicle in a static state. The effect of preload is shown in figure 3. Factors are measured on a test rig. The dynamic stiffness is represented dependent upon the amplitude for two different preloads for a constant excitation frequency. The non-linear dependence can be clearly recognised.

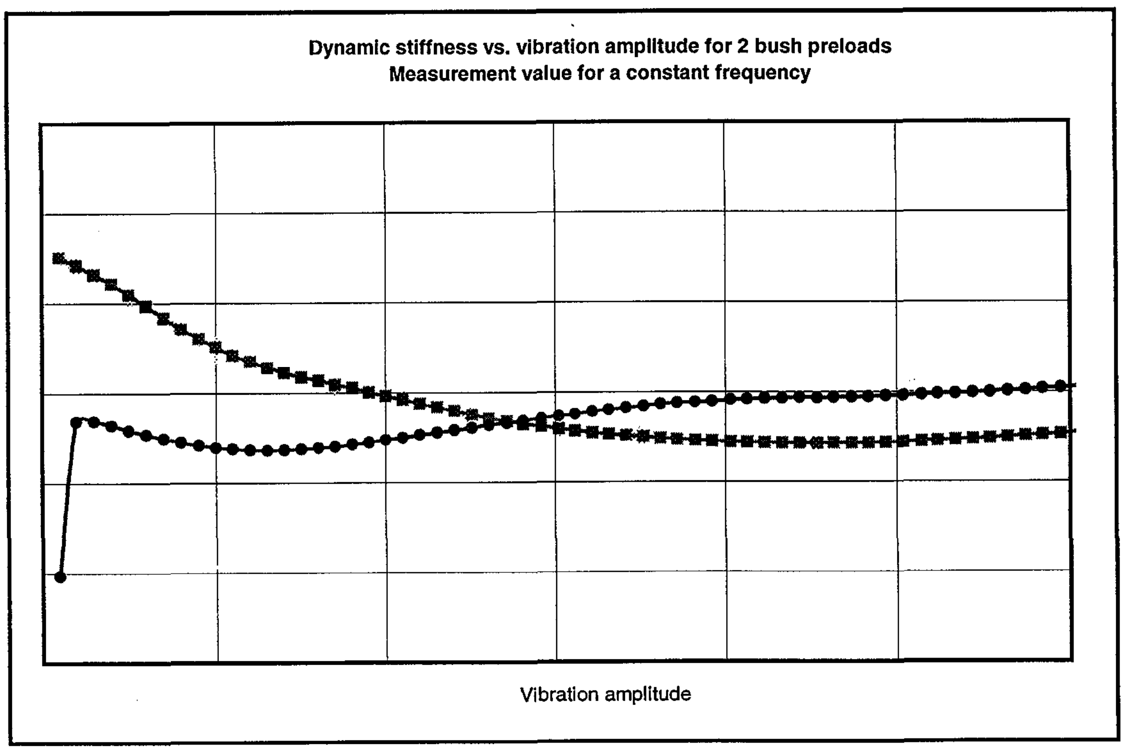


Figure 3: Dependence of dynamic stiffness on preload

Excitation Frequency

At this moment frequency dependence is not taken into account in the procedure presented here. This simplification, however, must be examined from case to case. Measurements have shown that the dynamic characteristic values increase with an increase in frequency and a decrease in distortion.

Vibration amplitude

Figure 4 shows the dynamic stiffness as a function of the vibration amplitude. Also shown are the real and imaginary parts. The illustrated curve is based on measurement results.

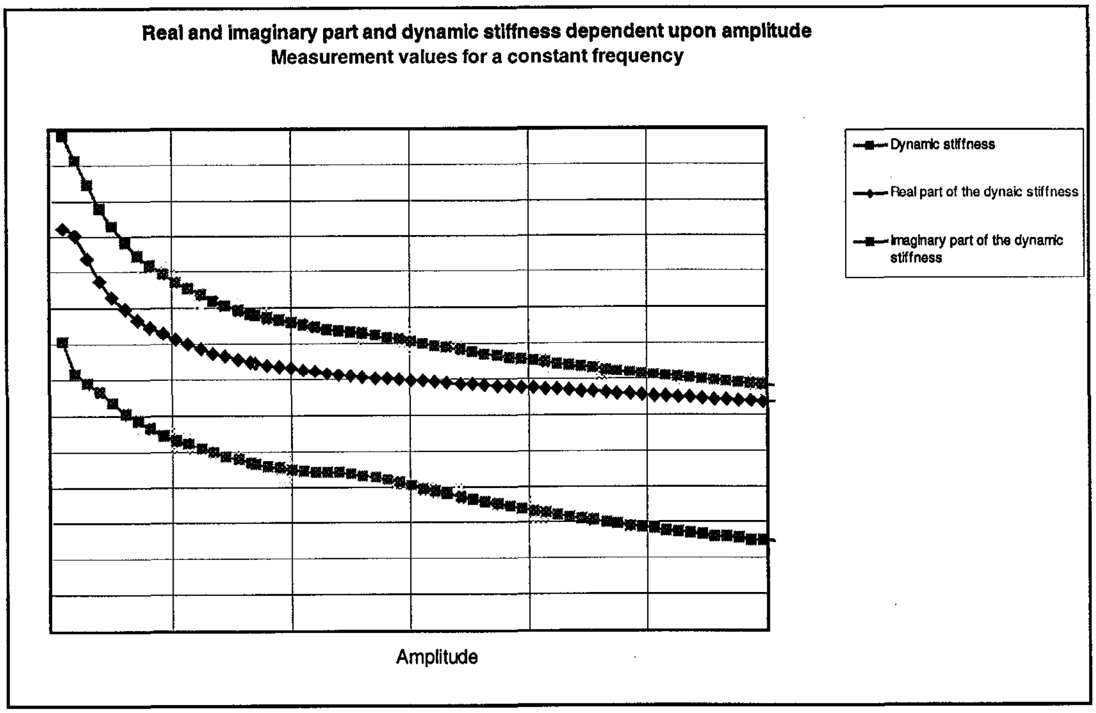


Figure 4: Dependence of dynamic stiffness on vibration amplitude

The non-linear effect dependent upon amplitude can be seen clearly here.

These results show that the measurement data for various preloads and amplitudes must be available before it is possible to perform an accurate frequency response analysis. The dynamic stiffness can then be determined separately from the measurement results for each excitation frequency.

4 Modelling of Bushes with MSC/NASTRAN

MSC/NASTRAN offers CELAS1 elements for the modelling of bushes. The damping used by these elements is material hysteretic damping. CBUSH elements are used for viscous damping.

CELAS1 and CBUSH elements consist of two nodes and refer to a property card (PELAS or PBUSH). One or more degrees of freedom for stiffness and damping can be given on both of these cards.

In a frequency response analysis, acceleration, for example, is calculated by means of the frequency. As previously shown, stiffness and damping are not identical for each amplitude and are therefore largely dependent upon the vibrational behaviour of the system. That means stiffness and damping can only be given exactly for one excitation frequency with use of the PELAS or PBUSH card.

From version 70, MSC/NASTRAN offers additional options through the introduction of PELAST and PBUSHT cards. Both of these cards refer to a TABELDi entry in which stiffness and damping are defined separately over a frequency range.

How the non-linear material behaviour of such spring/damping systems can be dealt with in a frequency response analysis is explained in more detail in the following section. The PELIT application (**PEL**AS **L**INEAR **IT**ERATION) was developed especially for this purpose. This automatically generates and modifies the corresponding NASTRAN cards.

5 The PELIT Application

PELIT is an application for the linearisation of rubber bush stiffness and damping around a defined operating point or for a larger frequency range in vehicle system analysis with MSC/NASTRAN SOL111. In order to use the application, the characteristic values of amplitudes and preloads for all relevant rubber bushes in the vehicle system model must be available.

Using a database containing the characteristic values, PELIT determines the accompanying values for the real and imaginary part of the complex stiffness for the displacement amplitudes in a frequency response analysis which occur in each rubber bush direction. The corresponding NASTRAN cards are then modified automatically with these new calculated values.
The calculation procedure is divided into two different steps:

1. Calculation of preload for each individual bush
2. Iterative linearisation process for calculating stiffness and damping for an excitation frequency.

5.1 Preload Calculation

The procedure is shown in Figure 5. For the preload calculation, a vehicle system model is fixed at the wheel contact points and analysed under its own weight. A static calculation with MSC/NASTRAN SOL101 delivers the displacements of all CELAS1/CBUSH nodes and issues these in a punch file.

PELIT then calculates the preload for each individual bush from the relative displacements of a CELAS1/CBUSH element and from the stiffness of the bush. At this moment the static stiffness is already linearised. It can be a result from a Multiple Body System. All results are summarised in a documentation file.

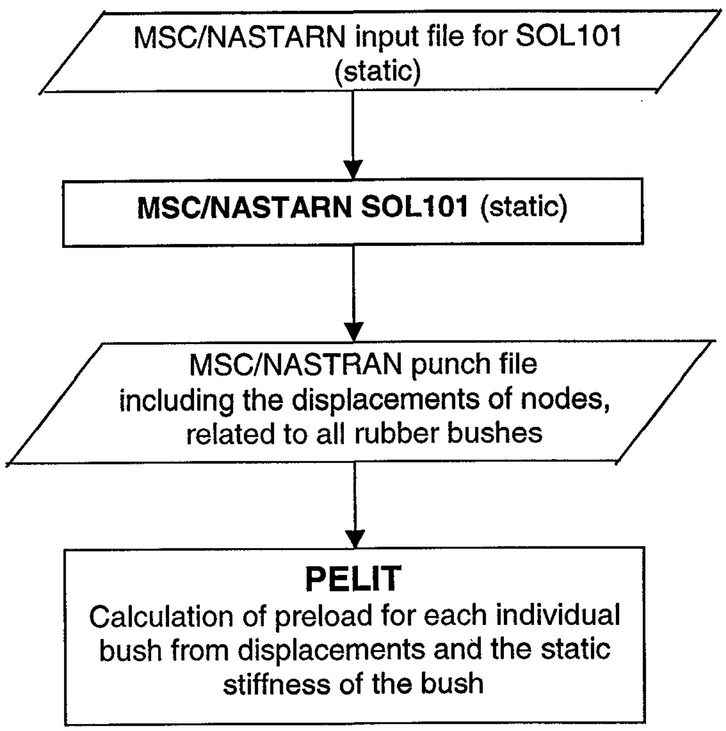


Figure 5: Preload calculation

5.2 Linearisation of the stiffness in a Frequency Response Analysis

In order to use PELIT, all relevant rubber bushes must be measured on the servo-hydraulic test rigs. The measured factors, stiffness and damping are available as a function of preload, amplitude and direction and stored in a database.

In regard to direction, it is important to note that the measured direction need not necessarily correspond to the degree of freedom in the FE model. Furthermore, data measurements for a bush on various directions (i.e. degree of freedom) may already be available in the bush database. The measurement values can be allocated to a bush by means of a bush name.

The principle procedure is shown in Figure 6.

The access to a bush of the FE model occurs by means of a property card. Depending on the application, these are PELAS, PELAST, PBUSH or PBUSHT entries. The following factors are allocated to each property card in an allocation file:

- Property number of the bush. This also means that the property may not refer to several elements
- Type of property card (PELAS, PELAST, PBUSH, PBUSHT)
- Bush name – i.e. allocation to measurement data from the database
- Degree of freedom of the bush
- Preload

<u>Determining the dynamic stiffness for the first calculation</u>

This is termed **<u>0. Iteration.</u>** Because no measurement values are usually available in the database for the exact calculated preload, linear interpolation is performed between the individual preloads. The starting value for stiffness and damping is the mean of <u>all</u> amplitudes. PELIT then modifies the NASTRAN record according to these newly calculated factors.

In a SOL111 calculation, MSC/NASTRAN determines the frequency response for the selected excitation spectrum. The results - i.e. the displacements of the nodes of the bushes – which should be linearised are written into a punch file. PELIT then reads in the complete NASTRAN input file as well as the results from the punch file.

Stiffness and damping are linear interpolated from the preload curves and the accompanying amplitudes. It is important here to note that the displacements of both bush nodes are usually not in phase. The maximum displacement between both nodes is therefore determined over a 360° phase angle. This maximum displacement corresponds to the amplitude which is used as the basis for the new calculation of stiffness and damping. PELIT subsequently modifies the bush values in the input record as well.

This loop, which occurs in the form of a MSC/NASTRAN calculation followed by the modification of the bush value using PELIT, is repeated until there are only minimal changes in the frequency response curve (Figure 6). It is important here to note that linearisation is performed only for one excitation frequency.

Between these iterative steps it is therefore necessary to represent the curve graphically in the form of a 2D plot, and to determine the frequency for which the bush values should be linearised. Because as a result of the modification of the bush stiffness, frequency displacement can occur while the individual iteration steps are being performed. P+Z uses the FE-Graph [1], a commercial tool the company itself has developed. For a driving comfort calculation, the examination of this frequency response takes place at comfort points which are selected by the user.

Automatic procedure

PELIT offers an automatic procedure in which the MSC/NASTRAN calculation and the modification of bush stiffness are performed automatically after each other. PELAST/PBUSHT cards in MSC/NASTRAN offer frequency dependent stiffness and damping. PELIT automatically updates these cards with each iteration.
The criteria for terminating the procedure is either a maximum number of iterative steps or a minimum change in bush values. Because these changes must be determined over a particular frequency range, the area below the curve of the TABLEDi card is used.

PELIT supports this entire calculation procedure with the following characteristics:

- Control over the complete Nastran input record in terms of input data format and how the individual cards relate to each other
- Automatic generation of the SET definition for all nodes of the bushes
- Documentation of all calculated factors by PELIT in a documentation file

  These are:
  - Preloads
  - Stiffness and damping for all iterations

- Reading in the bushes from the bush database and a table of all bushes containing the name of the bush, direction and preload.

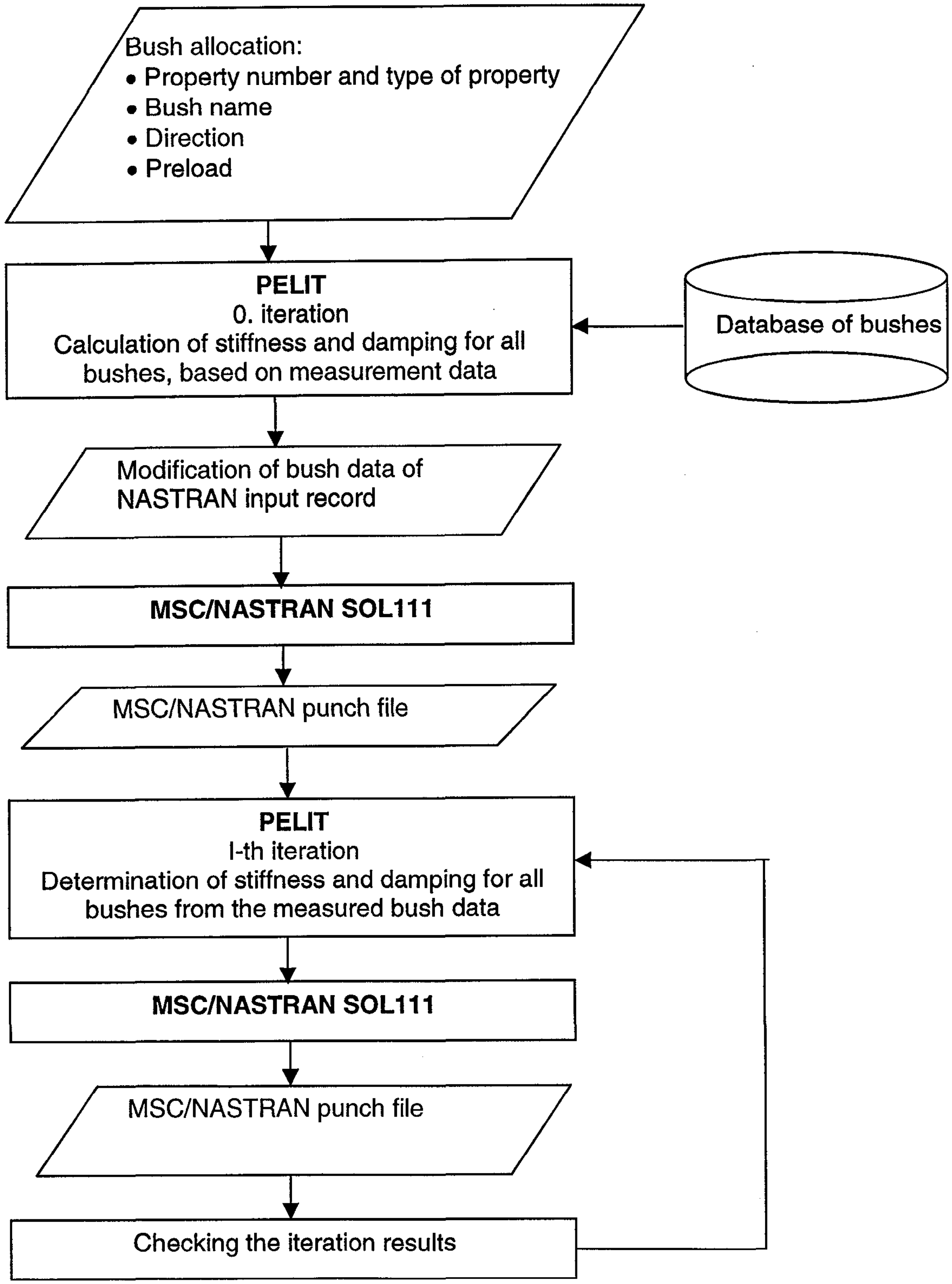
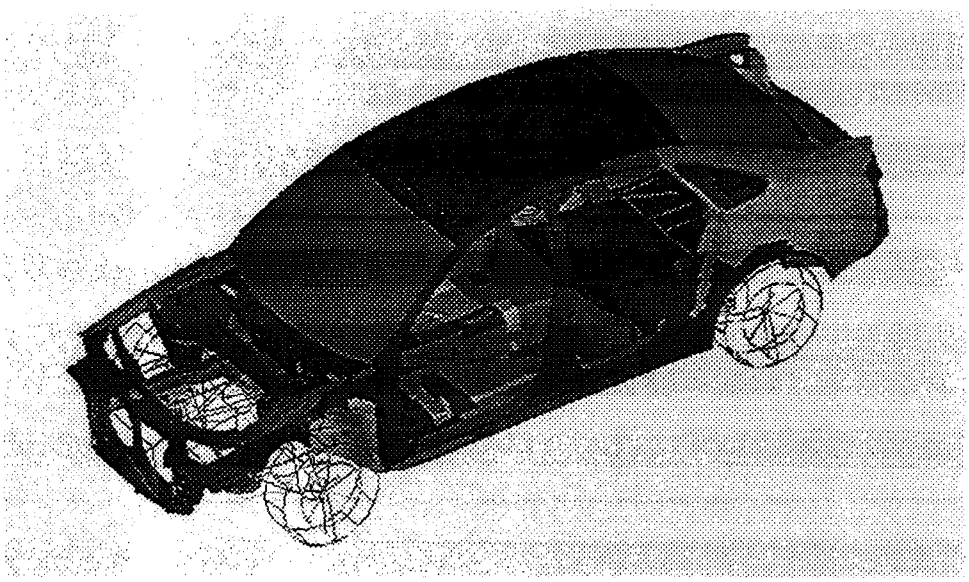


Figure 6: PELIT iteration process

6 Examples of Application

The results of a linearisation of dynamic stiffness are illustrated in an example. A FE vehicle model has been used. The FE model is shown in Figure 7. The performed calculation is only an example for demonstration of the procedure of PELIT.

Ten bushes (symmetric, 5 on every side) were modelled by means of rubber bushes in the region of the suspension. All of these were taken into account by PELIT in the iterations. Figure 7 shows only 5 bushes, 2 on the right side and 3 on the left side.



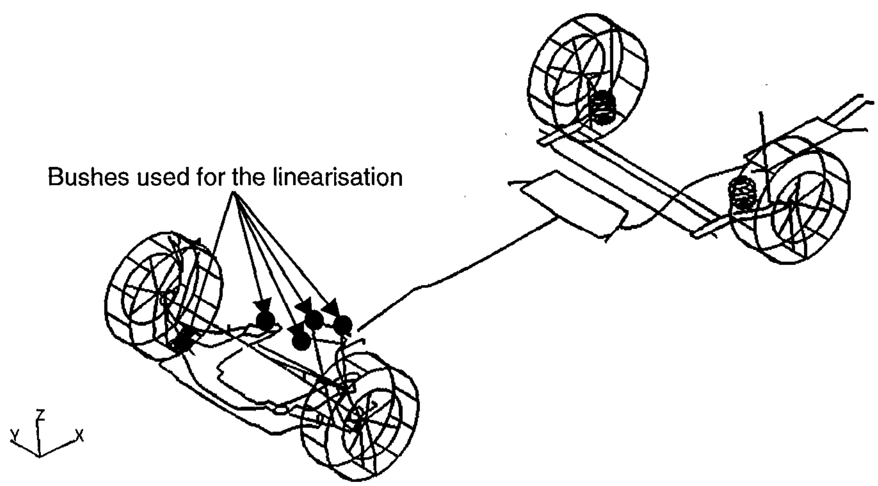


Figure 7: FE vehicle system model

This test load is a calculation of excitation with the engine idling. The vibration of the engine caused by excitation in idle mode leads to body acceleration, like shown in Figure 8. The bushes are modelled using CELAS1/PELAS cards in NASTRAN. A point at the seat rail was used as the comfort point for the evaluation of acceleration.

The maximum of the acceleration is shown in Figure 8. At these maximum a linearisation of all relevant bushes were performed. The calculations were performed as described above with **MSC/NASTRAN SOL111**. The results are illustrated below for iterations 0, 1, and 2. The effect of the modified bush stiffness can be clearly seen. Two iteration steps were necessary.

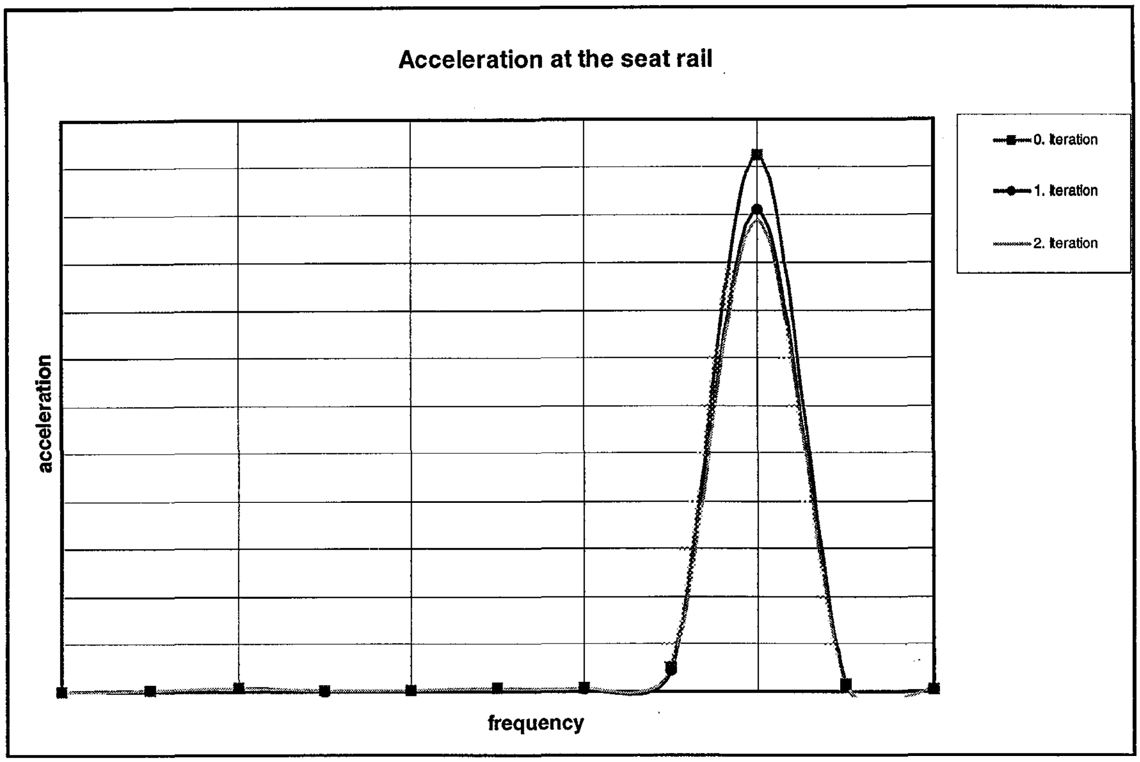


Figure 8: Acceleration at the seat rail

7 Conclusion

With the procedure described, it is possible to take into account material non-linear effects of rubber bushes in frequency response analyses. This requires an iterative process for determining amplitude-dependent stiffness and damping values on the basis of measured values. As a result it becomes possible to model the bush stiffness of rubber bushes in a frequency response analysis more accurate and therefore to evaluate the driving dynamics of a vehicle system model effectively on the basis of calculations.

The PELIT software described above was developed to support the user in the iteration process.

From version 70, MSC/NASTRAN offers PELAST and PBUSHT cards. These allow stiffness and damping values to be given variably over the entire frequency range. This procedure is also supported by PELIT. The primary disadvantage relating mainly to the CBUSH element is the significant increase in calculation time. No results are currently available regarding calculation time when using PBUSHT cards. This will become apparent with use in praxis.

8 Bibliography

[1] FE-GRAPH - Users manual. P+Z Engineering GmbH.