Development of a multiaxial elastomer bushing test bench with Hardware in the Loop (HiL) capability

Quasi-static and dynamic measurements to analyze multiaxial loading effects

Korbinian Thaler, Peter E. Pfeffer,
Munich University of Applied Sciences, Munich

Abstract
Bushings elements are widely used in the chassis of automotive vehicles. To receive information about the characteristics of the chassis, simulation models are used to conduct vehicle dynamic simulations in the developing process. The required bushing characteristics for these models are sensitive when it comes to simplification of the loading. To measure the characteristics of the bushing element under multiaxial loading, a multiaxial test-bench with beneficial test-routines was developed and is described in this paper. Thereby, exemplary results of quasi-static and dynamic measurements with multiaxial loadings are shown to confirm the relevance for such a test bench. At last the implementation of the HiL-application, regarding the simulation environment, used model for simulation and typical environmental inputs are explained.

Introduction
The elastomer materials used in bushings, have nonlinear characteristics for both displacement and frequencies. Therefore, it provides hysteretic responses for vibration excitations which differ from linear characteristics [1]. Furthermore, the bushing characteristics depends on the loading [2]. To obtain accurate results, which can be used in chassis simulation, a realistic characterization of bushing elements with multiaxial loading is necessary. Therefore the “Multiaxial Elastomer bushing Hardware in the Loop” (Multi-EL-HiL) test-bench was developed.
Overview of the Multi-EL-HiL test bench

I. Hardware of the Multi-EL-HiL test bench

The Multi-EL-HiL consists basically of two orthogonally arranged linear actuators combined with one rotational actuator, whereat the axis of rotation is collinear to one of the translational axes (Fig. 1.). Due to the design of the Multi-EL-HiL, it is possible to load bushings in all three dimensions simultaneously. The bushing is mounted in a fixture, by which the outer diameter of the bushing is stationary. All three actuators are connected to the inner part of the bushing, on which the required loading, in form of displacement or rotation, is applied. However, it was taken care, that the actuators are not connected directly between each other. There is always a degree of freedom for the movement of the actuator, without applying damaging force to one of the other actuators. The resulting force or torque is measured with a multicomponent dynamometer. The mentioned fixture of the bushing is mounted on the dynamometer, which can detect all three orthogonal components of a force, resulting from the loading of the bushing. The necessary power electronics for the control of the actuators is connected with the processor board DS1006 from dSpace to provide a real-time environment for the HiL tests. [3]

Fig. 1: Mechanical hardware parts of the Multi-EL-HiL test bench
1. Actuators

For the linear actuators two spindle drives (Exlar spindle FT35 in combination with a servomotor AKM64L from Kollmorgen) are used for loading the bushings with forces in lateral and axial direction. They can reach up to 5.5 kN for static loading, as well as 10.5 kN under dynamic use cases. In addition to the linear forces a rotatory actuator (servomotor AKM72K from Kollmorgen with a planetary gearbox PLN142 from Neugart) supplies torque up to 500 Nm for the rotatory loading. Depending on the importance of either max. velocity or max. torque it is possible to mount or dismount the gearbox. Hence, the Multi-EL-HiL is able to apply two linear forces up to 10.5 kN and a torque with 500 Nm simultaneously to the bushings. In the following tables (Tab. 1 and Tab. 2) the detailed performance specifications of the actuators are shown.

Tab 1: Performance specifications of the linear actuators

<table>
<thead>
<tr>
<th>Actuator type</th>
<th>Linear guided spindle actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Force</td>
<td>10.5 kN</td>
</tr>
<tr>
<td>Nom. Force</td>
<td>5.5 kN</td>
</tr>
<tr>
<td>Max. Velocity</td>
<td>1 m/s</td>
</tr>
<tr>
<td>System Clearance</td>
<td>&lt;0.06 mm</td>
</tr>
<tr>
<td>Spindle Accuracy</td>
<td>0.025/300 mm/mm</td>
</tr>
<tr>
<td>Actuator Control</td>
<td>8 kHz current control</td>
</tr>
<tr>
<td>Position Feedback</td>
<td>High resolution Sin-Cos-Encoder</td>
</tr>
</tbody>
</table>

Tab 2: Performance specification of the rotatory actuator

<table>
<thead>
<tr>
<th>Actuator type</th>
<th>AC servomotor</th>
<th>AC servomotor with gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Torque</td>
<td>90 Nm</td>
<td>1800 Nm</td>
</tr>
<tr>
<td>Nom. Torque</td>
<td>29 Nm</td>
<td>580 Nm</td>
</tr>
<tr>
<td>Max. Velocity</td>
<td>10.200 deg/s</td>
<td>510 deg/s</td>
</tr>
<tr>
<td>System Clearance</td>
<td>&lt;2 arcmin</td>
<td>&lt;6 arcmin</td>
</tr>
<tr>
<td>System Accuracy</td>
<td>20 arcsec</td>
<td></td>
</tr>
<tr>
<td>Actuator Control</td>
<td>8 kHz current control (max. latency of 125 µs)</td>
<td></td>
</tr>
<tr>
<td>Position Feedback</td>
<td>High resolution Sin-Cos-Encoder</td>
<td></td>
</tr>
</tbody>
</table>
2. Force and torque measurement
The measurement of the three orthogonal components of a force \((F_x, F_y, F_z)\), as well as the torque measurement \((M_z)\), is carried out through a multicomponent dynamometer from Kistler. This device works with four piezoelectric, three-component force sensors. A signal conditioner (also from Kistler) processes the measured signals and offers the forces and the torque in a range from +/- 10V. It is possible to calibrate the measuring range in different sensitivity areas. Therefore, the noise in small force signals can be minimized. [4]

In the analyses of the dynamic measurements, it is a necessity to consider the latency between the displacement/rotation and the force measurement. Due to small cycle durations at high frequencies, the latency of 2 ms must be corrected by suitable time shifting in post-processing. Also, for the HiL-capability it is important, that the latency is not higher than 5 ms, otherwise the system would be unstable. With a value of approximately 3 ms (latency force measurement + latency actuator control) the overall latency of the closed loop system is still in the permitted range and the force measurement is therefore usable for the intended HiL testing.

II. Software of the Multi-EL-HiL test bench
All functionalities of the Multi-EL-HiL test-bench are based on a Simulink model. By compiling this, the created sdf-file can be loaded on the real-time environment (processor board DS1006) of dSpace. Thereby it is possible to access and measure all parameters and values of the Simulink model via the software NextGeneration (Control Desk) of dSpace. There are blocksets included in the Simulink model which allow the control of the servo-amplifiers, as well as the calculation of the force/torque measurement signals, since it is necessary to calculate the equivalent value of force/torque to the existing input between +/- 10V. Also, the HiL environment is simulated in the Simulink model, which will be described later in detail.

In an offline optimization process the best controller parameters for the test routines used at the Multi-EL-HiL have been found. This optimization based on a fully developed Multi-EL-HiL model, which includes the mechanical and electrical actuator parts as well as a bushing model, a quarter vehicle model and the data communication.
Test routines
There are three test routines used with the Multi-EL-HiL for the characterization and functional validation of the bushings. However, before the beginning of a new measurement cycle, the bushings must be prepared via pre cycling. If there are no further specification given from the supplier, ten pre cycles with a velocity of 30mm/min and the measurement amplitude are applied to the bushing. The quasistatic and dynamic characterizations are state of the art for the measurement of bushings. They consist of triangular/sinusoidal displacement/rotation signals with a specified frequency and amplitude.

However, the possibility of dynamic multiaxial loading is not as common as one-dimensional, translational tests. The third test routine (HiL-test) is relatively new especially under multiaxial loading of the bushing. Therefore, the added value of the Multi-EL-HiL test bench lies in the dynamic multiaxiality and multiaxial HiL tests.

- Quasistatic characterization
During the quasistatic measurements of bushings the load is applied slowly, smoothly and steadily increasing until a specified limit is reached. The therefore used displacement/rotation velocity results out of a given test frequency between $10^{-5}$ and $10^{-1}$ Hz. [5]

By plotting the measured resulting force/torque over the applied displacement/rotation, a hysteresis is the outcome. For the determination of the static stiffness $C_{\text{stat}}$ the medium of the loading- and unloading curve must be calculated [6]. For higher displacements a typical curved shape of the characteristic is the outcome as well as an elliptical shape for very small displacements [7].

If the characteristic is approximated by a linear behavior, it is possible to generate a stiffness matrix (1), which shows the correlations between the different displacements/rotations and the resulting reaction forces/torques. Thus, the influence of a certain displacement/rotation can be evaluated, as well as compared to the other possible displacement/rotations.

$$
\begin{pmatrix}
F_x \\
F_y \\
F_z \\
M_x
\end{pmatrix}
= 
\begin{pmatrix}
k_{xx} & k_{yx} & k_{zx} & k_{x\phi} \\
k_{xy} & k_{yy} & k_{zy} & k_{y\phi} \\
k_{xz} & k_{yz} & k_{zz} & k_{z\phi} \\
k_{x\phi} & k_{y\phi} & k_{z\phi} & k_{\phi\phi}
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z \\
\phi
\end{pmatrix}
$$

(1)

In the following figure (Fig. 2.) an example of the influence, regarding multiaxial loading on the quasistatic axial characteristic of a bushing is shown. The measurement was carried out
with a sinusoidal displacement of 0.5 mm and 0.1 Hz, applied on the axial direction of the bushing. When the characterization without superimposed angle is completed, an additional static angle is applied in the rotational direction (Fig. 7.). At first +20 degree and subsequently -20 degree, which equals about +/- 45 Nm of torque, are applied to the bushing.

Fig. 2: Characterization of axial displacement with superimposed rotational angle

- **Dynamic characterization**

For the dynamic characterization, much higher frequencies are used in comparison to the quasistatic measurements. Because the handling and driving comfort is the primarily concern in this research, the maximum examined frequency is set at 30 Hz. By plotting the resulting force/torque over the applied displacement/rotation, a hysteresis is also the outcome. [7]

The ratio of the force/torque amplitude $F_a$ to the displacement/rotation amplitude $L_a$, resolves the value of the dynamic stiffness $C_{dyn}$ as shown in the following equation (2).

$$C_{dyn} = \frac{F_a}{L_a}$$ (2)
An additional characteristic value for a dynamic loading is the loss factor $d = \tan \delta$. The value $\delta$ stands thereby for the loss angle, which is the phase shift between the displacement/rotation and the force/torque, or the other way around, depending on whether the force/torque or the displacement/rotation is controlled [8]. For the calculation of the loss angle the ratio of the absolute damping $A_w$ to the product of $\pi$ and the amplitude of force/torque $F_a$ and displacement/rotation $L_a$ is needed (3). The value for the absolute damping corresponds with the enclosed area of the ellipse in the plotting of the dynamic hysteresis [8].

$$\delta = \arcsin \left( \frac{A_w}{F_a * L_a * \pi} \right)$$

(3)

In the following figure (Fig. 3.) an example of the influence, regarding multiaxial loading on the dynamic lateral characteristic of an engine mount is shown. The measurement was carried out with a sinusoidal displacement of 0.2 mm and 0 – 15 Hz, applied on the lateral Z-direction of the bushing. When the characterization without superimposed loading is completed, additional static displacements are applied (Fig. 8.). At first 7.0 mm in X-direction and subsequently 4.0 mm in Y-direction, which equals both times approximately 1.5 kN.

Fig. 3: Dynamic characterization of lateral displacement in Z-direction with superimposed force of 1.5 kN in X- and Y-direction
HiL measurements of the bushings

Hardware in the Loop (HiL) is the integration of real components and system models into a joint simulation environment. Thereby it is very important, that the simulation runs in real-time and is possible to depict the physical loads realistically [9]. For HiL measurements there are two systems necessary (Fig. 4.). At first the hardware environment, in which the tested component is fixed. And secondly the software environment, in which all components that are not present in reality are displayed as models [10]. At the Multi-EL-HiL the test-bench with the fixed bushing represents the hardware environment, whose inputs are the electrical actuators and outputs are the measured forces/torque of the multicomponent dynamometer. On the real-time environment, the rest of the vehicle is displayed as several models. These compute a displacement of the bushing according to the given inputs. After loading the bushing, using the actuators, the resulting forces/torques are given back to the models whereby new displacements result.

Fig. 4: Test environment Multi-EL-HiL test bench

The hardware environment is already operational as described in the previous chapters. For the software environment it is necessary to generate an environmental input and a vehicle model, which computes the appropriate displacement of the bushing. Because the first tested bushing is an engine mount the vehicle model must calculate the relative displacement between the engine and the car body. In the first step the HiL measurements will be done with only one dimension. In the next steps further dimensions will be added to the HiL environment. The used environmental input is the irregularity of the road and is given as the power spectral density of a synthetic road surface resulting from a filter-based road profile generator [11]. With this generator any road classification with its correlating power spectrum density,
road length and tire filtering effect \cite{12} is possible. In figure 5 an example of a generated road, used for HiL tests is shown.

![Power spectral density of a synthetic road surface for Multi-EL-HiL tests](image)

**Fig. 5:** Power spectral density of a synthetic road surface for Multi-EL-HiL tests

The engine was an electric motor, therefore the high frequency excitations of this motor are neglected in this simulation. Building on this, three Degrees of Freedom (DoF) are necessary to calculate the displacement of the engine mount out of the road profile (Fig. 6.). The displacement of the wheel \(x_W\) is simulated, using the unevenness road profile from the previously shown road as the environmental input \(u\). Simultaneously the simulation of the consequential displacement of the car body \(x_C\) and the simulation of the displacement of the engine \(x_E\) is carried out. For the latter the resulting force of the bushing is needed. Therefore, the relative displacement between the simulated displacement of the car body and the engine is applied to the tested bushing, whereby the measured forces can be fed back to the simulation of the quarter vehicle model. From that, new displacements are calculated and by applying this new displacement again on the bushing, the HiL environment is closed. The same approach can be used for vehicle handling simulation. Due to the lower frequencies up to 3 Hz, the required performance of the Multi-EL-HiL is significantly lower.

**Fig. 6: Vehicle model for simulating the displacement of the engine mount**

**Conclusion**

With the Multi-EL-HiL a successfully implemented concept of a multiaxial bushing test bench is presented, which is capable of measuring the force/torque and displacement/rotation with a very high accuracy. The focus lies on characterizing and measuring with multiaxial loading, as well as executing real-time capable HiL tests. For this purpose, the hard- and software components have been developed to fulfill real-time requirements. The actuators and guiding systems were developed to ensure best actuator control behavior. In addition, the actuator controller communicates via a fiber optic system, which guarantees a very low latency of the open and closed loop control.

The bushing test scenarios are split in characterization and HiL tests. For e.g. bushing HiL tests, measured and synthetic road surfaces can be used. The actuator controllers perform very well for all quasistatic and dynamic bushing tests. With the developed Multi-EL-HiL test bench and the test scenarios, the developing process of bushings can be accelerated and enhanced.
References