The Influence of Yaw Movements on the Rating of the Subjective Impression of Driving

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Abstract

Today's automotive engineering is strongly affected by the assignment of modern electronics. Here mainly the field of driver assistance systems becomes more and more important. Without using simulation methods the development of these systems is nearly unimaginable. On the other hand the progress in the classic field of vehicle dynamics is advanced in a way, which makes bigger steps increasingly unplausible.

The development of assistance systems makes the human being as the directly concerned component irreplaceable in the development process. Here the use of driving simulators has become an essential element, because they offer the possibility to integrate the human being as a real part into the simulation environment.

In many cases the reaction of the driver depends on the visual and the mechanical information he gets from the current driving situation. Therefore mainly in critical situations the quality of the information contributes to the characteristic of the driver's reaction. Looking at the mechanical part driving simulators often have problems with presenting several kinds of manoeuvres including for example an acceleration step, whose amplitude lasts for a longer time (full braking, step steering, etc.). One main reason can be found in the difficulties caused by the superposition of the translation and the rotation of the driver's cab in consideration of the motion systems kinematics and dynamics. The idea of an extensive abandonment of the rotation leads to several possible options. One of these options consists in the use of yaw movements to compensate the needed workspace of the motion system in comparison to the presentation of sustained accelerations via angular movements with a stewart-plattform or other kinds of tilting systems.

The paper deals with the influence of different scaled yaw movements on the rating of the subjective impression of driving. Extensive test series have been made with a 1-DOF-system, which puts the test person into a simulation environment. Different kinds of drivers (from everyday drivers to professional test drivers) had to pass different driving situations to rate them subsequent via questionnaire or pushbutton. Assuming that higher yaw rates are acceptable for the driver this should be a kind of a worst-case scenario, because nearly every driving situation, which contains yaw movements, is connected to the appearance of

sway accelerations. This is the most important mechanical control variable when driving a vehicle and will probably raise the acceptable yaw rates.

In the next step this simulator with its yaw table has been mounted on a stewart-plattform hardware- and software-sided. This assembly works properly under normal driving conditions, but reaches its dynamic limits rather fast when adjusting higher yaw rates. For this research purpose the use of the described configuration of the motion system is restricted to accurately defined driving manoeuvres, which require a special motion setup, a suitable database and well instructed test persons.

At present we prepare a test series to get more information about the influence of sway acceleration on the subjective rating of different scaled yaw rates. This may lead to new approaches in the development of motion systems and motion algorithms.

Introduction

Today's automotive engineering is characterized by decreasing product cycles in combination with high cost pressure. On the other hand the development process benefits from permanent increasing computer power. This leads to the possibility to design components of a vehicle only by using modern simulation methods. For example in the field of vehicle dynamics this makes it possible to create a certain driving behaviour, whose characteristics are defined by theoretical parameters and characteristic curves. However it is not clear whether the feeling of a human driver correlates with the theoretically calculated characteristic. From this it follows that at this stage the human being as the directly concerned component is irreplaceable in the development process. Here driving simulators offer the possibility to integrate the human being as a real part into the simulation environment at a time, when hardware components are not yet available.

Presentation of Motion

The reaction of the driver depends on the visual and the mechanical information he gets from the current driving situation. Therefore mainly in critical situations the quality of the information contributes to the characteristic of the driver's reaction. Looking at the mechanical part of the provided information driving simulators often have difficulties with presenting several kinds of manoeuvres including for example an acceleration step, whose amplitude lasts for a longer time (full braking, step steering, etc.). One main reason can be found in the difficulties caused by the superposition of the translatory and rotatory movements of the driver's cab in consideration of the motion systems kinematics and dynamics. Figures 1 and 2 illustrate the described difficulty by means of two examples for basic movements providing an acceleration impression during a braking maneuver based on traditional (classical) washout algorithms [1]. The first figure shows a superimposed motion with a pivot in the area of the driver's head. The diagram on the left shows a typical run of the respective perceived acceleration $a_{x,sens}$. The data has been taken from measurements at a truck driving simulator, where the driver's cab has been mounted on a Stewart-platform [2].

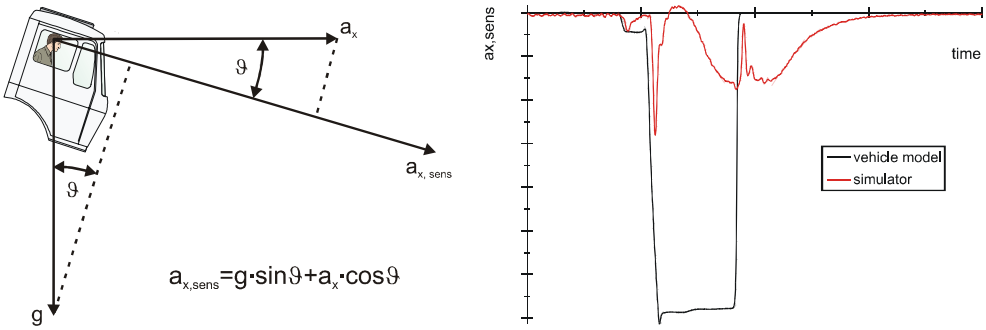


Figure 1: Superposition of high and low frequent acceleration sections

The following figure indicates the influence of an excentric pivot during an angular movement. The motion system providing the data for the diagram has also been taken from a truck driving simulator. In this example the motion system consisted of diagonally arranged ramps [2], which results in the nontypical pivot above the driver's head.

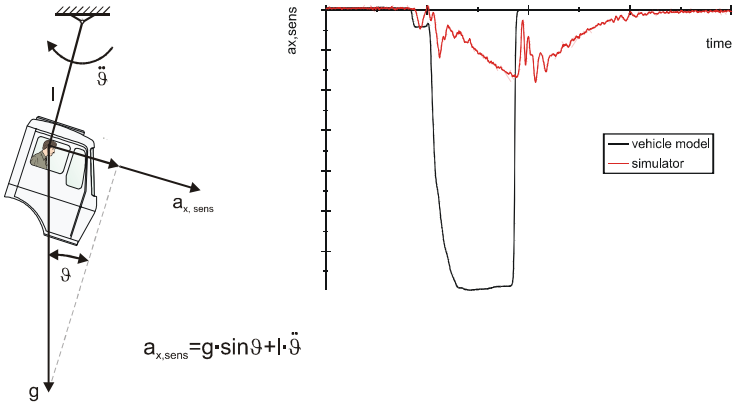
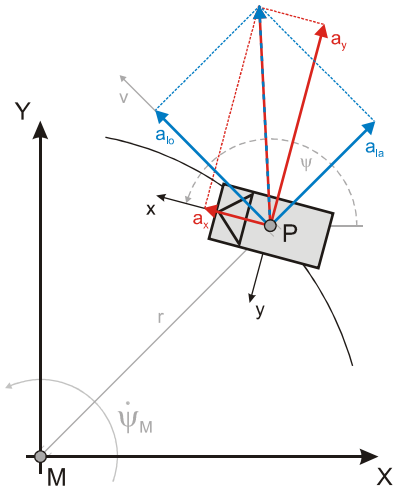


Figure 2: Influence of excentric pivotal point

The exclusive use of angular movements raises the role of the position of the pivot, which rapidly leads to the conclusion that standard motion systems are not adequate. Furthermore the rotation is hardly restricted to angular accelerations lower than the respective threshold of perception and the maximum presentable acceleration (AUBERT-effect).

The abandonment of pitch and roll movements for simulating sustained force cues leads to several possible options. One of these options consists in the use of yaw movements to compensate the needed workspace of the motion system in comparison to the presentation of sustained accelerations via angular movements with a Stewart-platform or other kinds of tilting systems. Therefore the main acceleration impression has to be presented via movements on an x-y-plane, e.g. with an x-y-table or a special kind of vehicle. Figure 3 shows the superimposed and transformed acceleration vectors at a possible driver's cab.



Lateral acceleration:

$$\vec{a}_{la} = \frac{\vec{v}^2}{\vec{r}}$$

Tangential velocity:

$$\vec{v} = \dot{\psi}_M \cdot \vec{r}$$

Resulting acceleration:

$$\vec{a}_{la} + \vec{a}_{lo} = \vec{a}_x + \vec{a}_y$$

Transformation of coordinate systems:

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \begin{pmatrix} \ddot{X} \\ \ddot{Y} \end{pmatrix}$$

Figure 3: Acceleration vectors at driver's cab

It is obvious that an additional rotation of the driver's cab moving on a circular path with a certain radius r at a particular time t leads to another distribution of the resulting acceleration vector a. That means that at the time t the angle between the longitudinal axis of the cab and the tangential velocity vector defines the longitudinal and the lateral acceleration impression of the driver. Here the importance of the position of the drivers head has to be pointed out, because movements causing CORIOLIS-effects have to be minimized.

Without going into more detail is becomes clear that the most critical factor of this kind of motion presentation is the movement in yaw-direction. A human being perceives yaw movements in different ways. Yaw velocities are mainly perceived visually, whereas the perception of yaw accelerations takes place in the vestibular organ (→ cupula). Also mechanical receptors (mainly shear stresses and retention forces) contribute a small part to yaw movement perception. The basic considerations have been made by STEINHAUSEN (1931), who described the functionality of the cupula as a overcritical damped torsion pendulum [4].

From this it follows that - when producing motion impressions only via the described x-y-movements - the presented yaw rates do not always come up to those resulting from the actual dynamic vehicle state.

Experimental setup

To get more information about the perception or the possibilities to scale yaw movements a 1-DOF-simulator has been built up. It provides a fully equipped driving environment. Among the driver's seat, which is placed in the center of rotation, and the operating elements the visual scenario is displayed via three flat screens, the driving noise via a surround sound system. Additional measurement equipment is located in the back, see figure 4. The drive of the cab has been realized with an AC-servomotor with two subsequent transmission gearings. In this configuration the drive unit is able to accelerate the cab with more than 1000 deg/s² up to a yaw velocity of about 125 deg/s. The powerful motor also allows the drive of assemblies with higher moments of inertia, e.g. when realizing an excentric position of the cab.

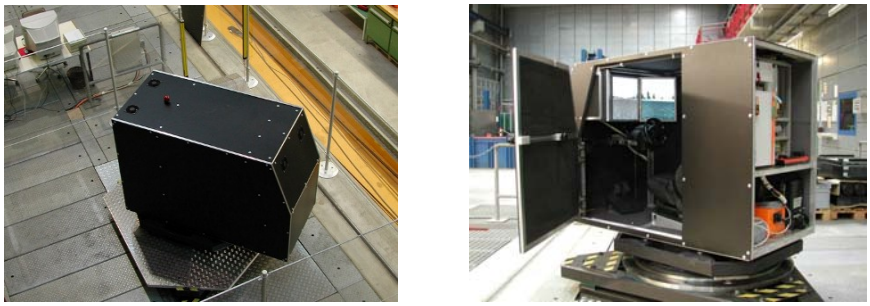


Figure 4: 1-DOF-system

For calculating the vehicle dynamics an internal developed tool has been used [3]. This simulation program is an interactive tool, which makes it possible to simulate the drive of the entire vehicle within a virtual environment in real-time.

Test program

Under consideration of the limitations predefined by the electric motor (performance data, frequency response, etc.) an extensive test program has been made, whose most important parts are presented below.

To get an idea about the possibilities of tricking the human beings perception a characteristic diagram has been specified. It contains test points, which indicate the absolute presented acceleration in the first column ($\ddot{\psi}_{in} = 0$ deg/s²) and the ratio between the calculated ($\ddot{\psi}_{in}$) and the presented ($\ddot{\psi}_{out}$) values of the yaw velocity and acceleration respectively in the other columns.

Figure 5 shows main parts of this diagram with the calculated value resulting from the current vehicle dynamic state on the x-axis.

Table 1: Overview over test points

$\ddot{\psi}_{out}$ [deg/s²]							
	24	-	-	…	4.00	…	2.00
	…	…	…	…	…	…	…
	4	1.00	1,00	…	0.67	…	0.33
	…	…	…	…	…	…	…
	0	0.00	0.00	…	0.00	…	0.00
	…	…	…	…	…	…	…
	-2	-2.00	-2.00	…	-0.33	…	-0.17
	...	…	…	…	…	…	…
	-4	-4.00	-4.00	…	-0.67	…	-0.33
		0	1	...	6	…	12
		$\ddot{\psi}_{in}$ [deg/s²]					

The diagram shows test points, which had been analyzed within the scope of this study. The selection of these points has been made by taking the following main aspects into account:

- max. calculated yaw acceleration of $|\ddot{\psi}_{in}| = 12$ deg/s²
- max. calculated lateral acceleration of $a_y = 8$ m/s²
- drive on clothoid shaped curves (clothoid angle $\tau = 67.5$ deg)
- constant driving speed

Clothoid shaped curves have the property of providing a constant absolute value of the yaw acceleration, which makes them a basic element in road construction. Figure 5 shows a vertex clothoid with a typical run of the yaw acceleration and the lateral acceleration.

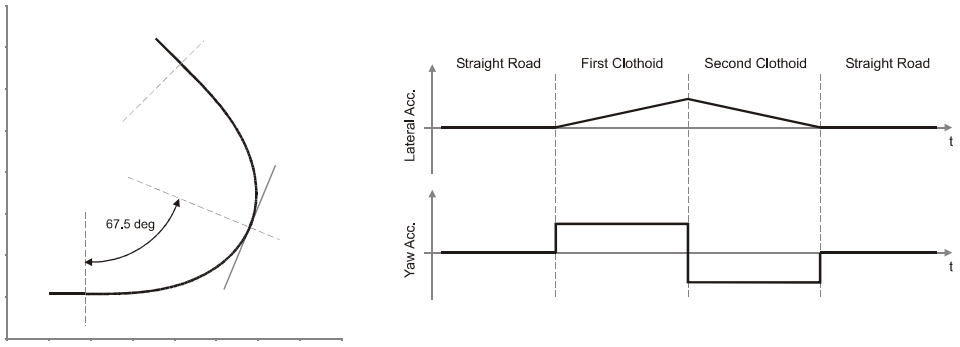


Figure 5: Vertex clothoid

Granted that the driving speed is constant the run of the curve is clearly defined and can be calculated. Afterwards a database with a certain distribution of these curves can be designed considering the specified test points.

Figure 6 shows the resulting database, where the clothoid is the only curve shape. The longer straight segments correspond to the column $\ddot{\psi}_{in} = 0$ deg/s² in table 1, which leads to an offset-movement in this particular case and is therefore a basic test in motion perception. The numerical values in the picture on the left, which gives an overview over the used database, indicate the absolute yaw acceleration, when passing through the curve in the middle of the road.

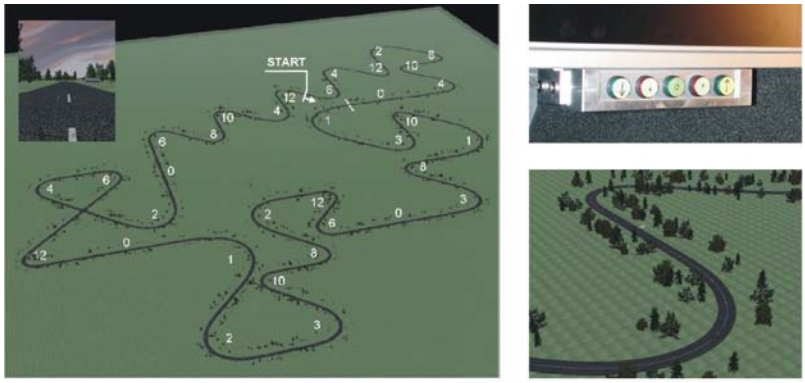


Figure 6: Database with driver's view, zoom and pushbuttons

The proving ground consists of 34 vertex clothoids with 5s-sections in-between. The used vehicle model within the simulation program has had the driving characteristic of a middle class passenger car.

Corresponding to the characteristic diagram it has to be circled about 3 times (value differs a little between preliminary tests and the main test). Because of the high demands on the perceptive faculty and the resulting physiological stress (→ motion sickness) a longer pause of about half an hour after every circuit has been scheduled.

The rating of the presented yaw movement has been made via pushbutton. Five categories have been distinguished. The number in the fourth column characterizes the category and has later been used in the analysis, see figure 8.

Table 2: Rating categories

category	description	colour	no.
a lot too much	clearly perceptible and very unpleasant	red	2
a little too much	perceptible, but not unpleasant	yellow	1
ok	comes up to the expectations	green	0
a little too little	perceptible, but not unpleasant	yellow	-1
a lot too little	clearly perceptible and very unpleasant	red	-2

The individual scaling/offset-factors being adjusted for every curve have been chosen randomly to avoid systematic errors. Also every test driver has obtained its own permutation sequence. The change of these factors has happened during the straight 5s-sections, where the test subjects had to rate the previous occurrence, via a ramp function.

After several preliminary tests for narrowing the general field of research down to a reasonable testing area (→ test objective, characteristic diagram, layout of simulation environment, statistic significance, etc.) the main test started with an intensive briefing of the test subjects. 40 people had participated in this study, 26 everyday drivers and 14 professional test drivers. All of them had been instructed days before via verbal briefing and handout. They had also the possibility to drive with the simulator to get a better understanding of what is demanded during the main test. In particular the importance of an anticipatory driving technique had to be pointed out. Every high frequent input via the steering wheel would have had changed the position of this particular test point in the characteristic diagram and therefore could have had great influence on the acceptance of the presented motion.

The test drivers had to operate the steering wheel and the pedals on their own, because in a possible later simulator they will have to do it also themselves. The maximum driving speed has been fixed via a certain gear ratio within the vehicle model. The test subjects had been requested to drive with max. speed except that they have any kind of difficulties or need a break (note: this did not happen). Figure 7 shows an example of the run of the yaw velocity and the yaw acceleration while a test subject is driving through two curves on the database (compare figure 6: ‘3’ and ‘10’).

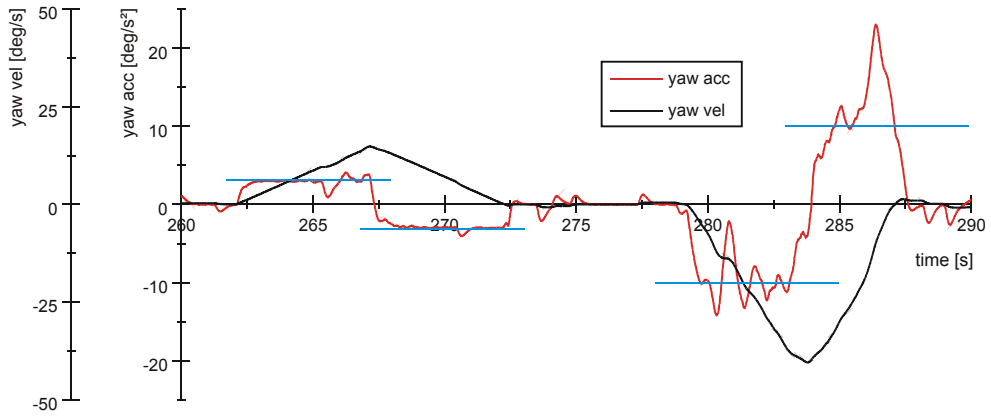


Figure 7: Drive of a test driver through two vertex clothoids

It becomes clear that the ideal run of the curves (see figure 5) is nearly not reachable when the driver is driving on his own. This also underlines the importance of the already mentioned way of driving.

Test results

Figure 8 shows the result of this test series averaged over all participants. The areas divided by the black lines correspond to the chosen categories. The small numbers in the diagram give a detailed information about the averaged rating of every test point (from '-2' → *a lot too little* up to '2' → *a lot too much*, see table 2).

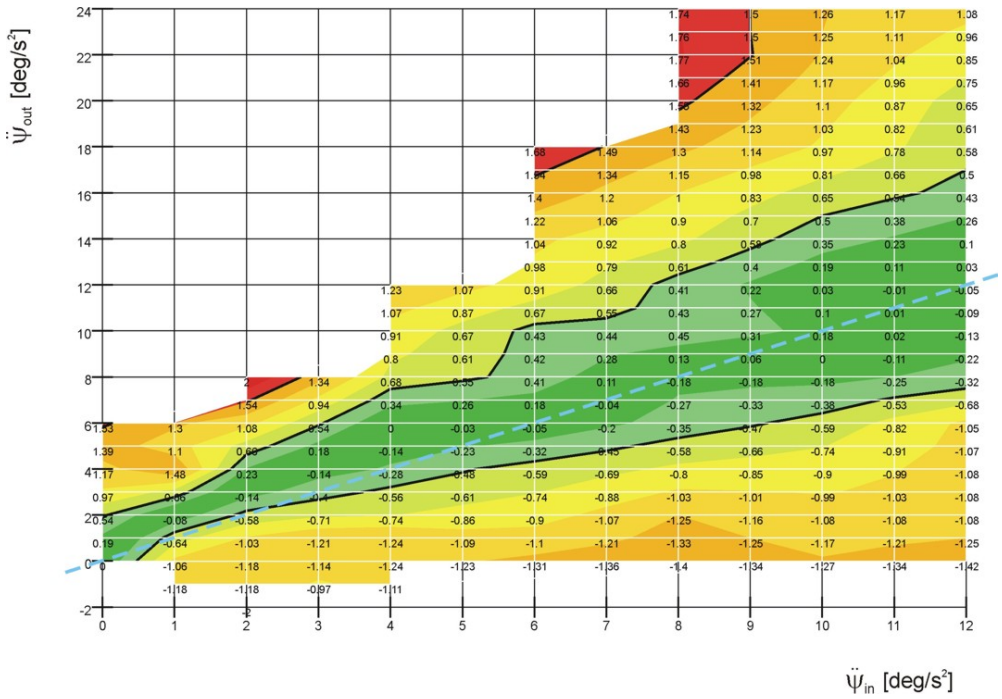


Figure 8: Averaged ratings of all participants

The blue dashed line indicates the points, where the yaw acceleration is presented true to scale. First of all it is cognizable that there is a green corridor around the scale factor 1. In a short section at lower input-values the corridor sits a little above the dashed line. Looking at output values lower than true to scale the not acceptable area (→ red) is not reached.

Negative scaled values are possible within the limits of the threshold of perception but not relevant in practical use. They require an extreme smooth way of handling the operating elements, which is not realistic in everyday more or less unpredictable traffic situations and the individual control behaviour of the driver. From another test within this test series we had an indication about the threshold of perception for yaw accelerations when driving only visually on a straight road. In this test the drivers had to accelerate the car on their own and to lay their hands also on the steering wheel, where a pushbutton was placed. That means that the detection of a yaw movement was a task in addition to the driving task. As a result a value of about 2.5 deg/s² came out, which is – as expected – higher than most of the other values, which can be found in the literature. Looking at the diagram it is obvious that the point of intersection between the upper black line and the ordinate is in a comparable area. When comparing the two types of test drivers it is observable that for the professional drivers the corridor is narrower and a little displaced to lower acceptance limits.

To consider the distribution of the valuations confidence intervals have been calculated for every test point. Therefore probability values of 5%, 1% and 0.1% have been determined. Assuming that an incidental stay in the yellow area is acceptable the upper interval limit of the upper yellow area and the lower interval limit of the lower yellow area define the acceptance of a test point. As a result of these considerations figure 9 shows possible offset / scaling factors versus the input acceleration for a probability value of 0.1%.

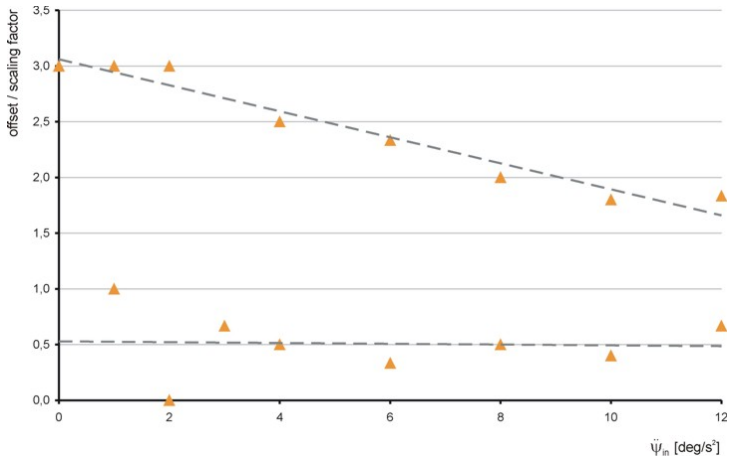


Figure 9: Acceptable offset/scaling factors

It is visible that the lower limit of the acceptance area can be approximated by a horizontal line, which indicates a constant scaling factor of about 0.5 . The upper limit can also be approximated by a straight line, however this one is falling down from factor 3 to a factor of about 1.7 at 12 deg/s². Other tests consisting of everyday driving situations - like a lane change maneuvers – had shown similar results.

As mentioned before the test is kind of a worst case scenario for this research purpose, because nearly every driving situation, which contains yaw movements, is connected to the appearance of lateral accelerations [5]. This is the most important mechanical control variable when driving a vehicle and may therefore raise the acceptable yaw rates.

Further Reflections

To get more information about the influence of a superposed sway acceleration impression the simulator with its yaw table has been mounted on a Stewart platform hardware- and software-sided. Figure 10 shows two pictures and a CAD-drawing of the simulator.

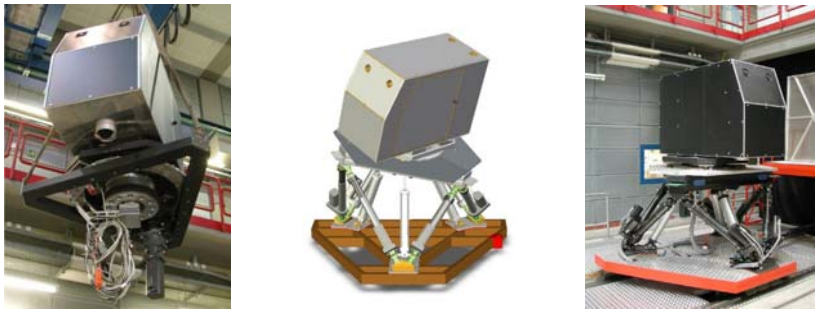


Figure 10: Assembly of yaw table on Stewart platform

This layout of the simulator works somewhat properly under normal driving conditions, but reaches its dynamic limits rather fast when making higher frequent inputs or adjusting higher yaw rates. Therefore the use of the described configuration is restricted to accurately defined driving manoeuvres, which require a special motion setup, a suitable database and well instructed test subjects.

At present we prepare a test series to get more information about the influence of sway acceleration on the subjective rating of different scaled yaw rates. The following figure shows the path of a 180-degrees vertex clothoid and the corresponding angular positions of the driver’s cab at different points on the curve with double yaw rate.

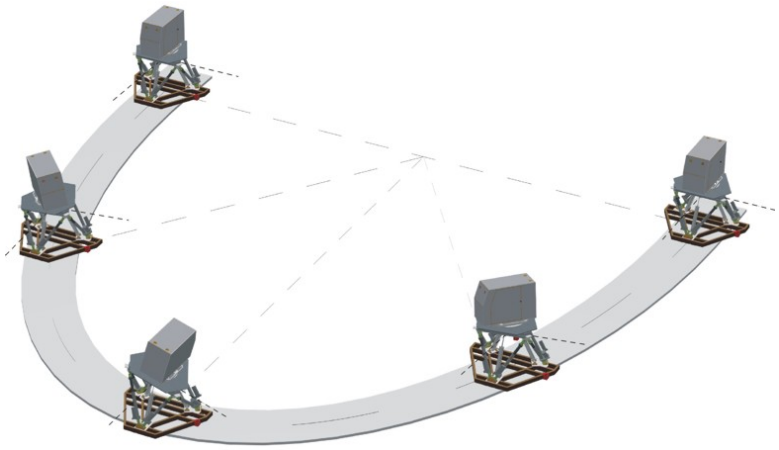


Figure 11: Superimposed motion with double yaw rate

First preliminary tests have shown that a superposition with an acceleration in sway has positive effect on the possibility of varying the movement in yaw. This might lead to more tolerance in the design of applicable motion systems and motion algorithms, when thinking of this kind of motion presentation.

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