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The Application of Moving Base Systems in Driving Simulators with Special Regard to the Sensation of Yaw Movements

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Abstract: Driving simulators involve the capability of simulating critical and dangerous driving situations up to the limits of active safety. They are employed for investigating the interactions of the driver-vehicle system under reproducible and non-dangerous conditions. Because of their flexibility they are well established in scientific research. They are mainly used in current automotive fields of research like driver assistance and autonomous driving systems. 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. It must be considered that the circuit of information has to be the same as under real driving conditions. Otherwise the results are not transferable. This paper deals with the possibilities of presenting all information to the driver, which are necessary to give him a realistic impression of driving. A main subject is the sensation of yaw-movements, which could be of interest when novel kinds of moving base systems are designed.

Key words: Driving simulator, yaw movements, thresholds of perception.

1. The Information Loop Driver-Vehicle

In a driving simulator the driver should be exposed to the same circuit of information, see Fig. 1, as in case of driving a real vehicle so that a comparable reaction can be expected. Instead of the fully engineered vehicle, however, technical devices are used as substitutes to provide suitable information.

In order to present this information to the driver, an important part of the simulation system is the driving environment, which acts as an interface to the human being. Besides the visual and haptic information the motion, which means the vestibular information, is one of the most important ones. In many cases the reaction of the driver depends on the visual and the mechanical information that 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.

2. Sensation of Accelerations

The importance of simulating motion in a driving simulator is caused by the fact that without motion simulation it often comes to the phenomenon called cinesia-motion sickness. Cinesia appears, if there is a discrepancy within the sensory perception. That is the case, when the visual information channel is aware of other movements than the vestibular channel. Cinesia effects occur, if e.g. a passenger in a vehicle reads a newspaper. While a static picture is visually conveyed, the driver receives, however, via his vestibular organ a motion information. This discrepancy at the sensory

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perception can lead to nausea. However, the medical causes are not cleared completely yet.

Not only the correct representation of the individual parameters but especially the correct phase behavior of all simulated information is relevant to avoid cinesia effects. Furthermore it has to be taken into account for the layout of motion but superimposed. For example, the appearance of a sway acceleration is nearly always in combination with a yaw movement.

To be able to specify the requirements for motion systems under consideration of the sensory perception of the human being more exactly, it is advantageous to understand, how the sense organs work [1], which are responsible for motion perception. Because this work especially focuses on the effect of different scaled yaw movements on the rating of the subjective impression of driving, more details of the working principle of the cupula have to be explained.

Acceleration forces are predominantly sensed with the organ of equilibrium. This vestibular organ is placed in the middle ear, auris media. There we find the cupula for sensing rotational and the macula for sensing translational accelerations, see Fig. 2.

Regarding the rotational part we can see three semi-circular channels according to the main axes. When rotating the endolymph inside will move and stimulate the cupula, see Fig. 3. This acceleration causes a deflection of the cupula after a short stay due

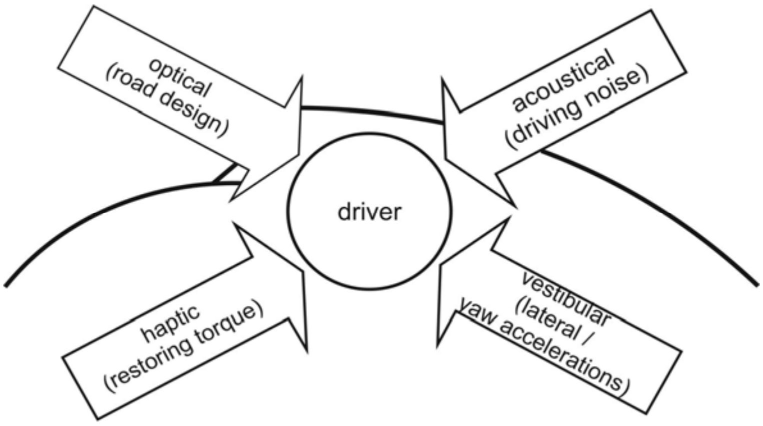


Fig. 1 Information sensed by the driver.

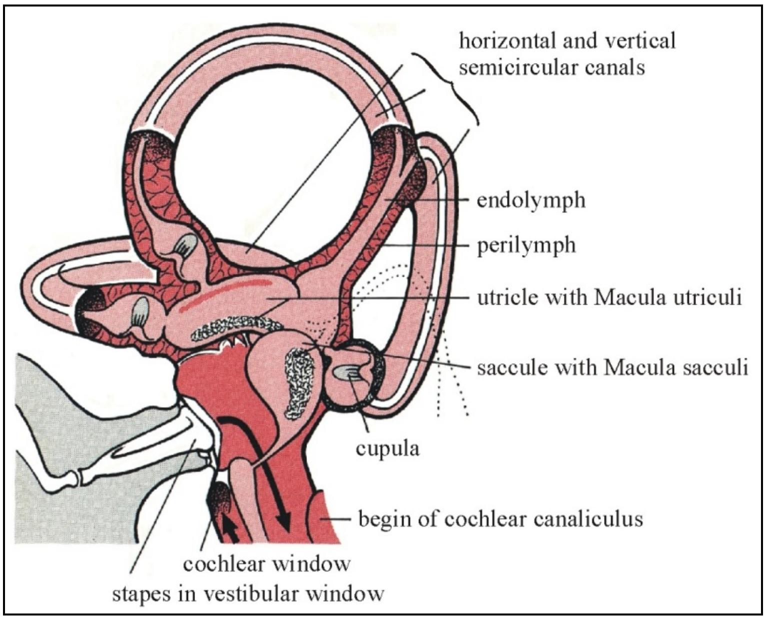


Fig. 2 Organ of equilibrium.

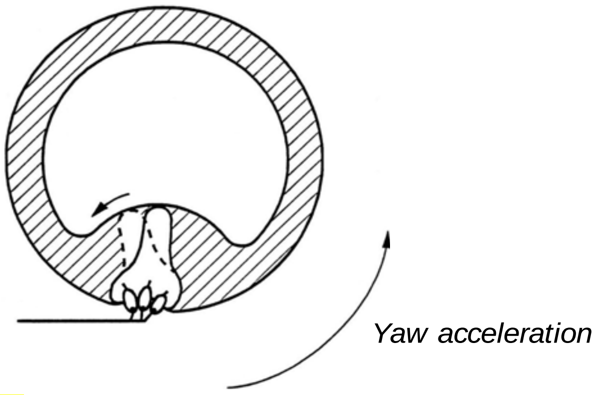


Fig. 3 Cupula.

to its inertia.

In the beginning the afferent nerve activity is proportional to the yaw velocity and will later decrease when this velocity does not change anymore. This results from the lymph following slowly the rotational movement until there is no difference between the rotation of the head and the lymph anymore. Due to this friction inside the semicircular canals long lasting slow rotational movements are not sensed by the vestibular organ [2].

Figs. 4 and 5 give an impression of the behavior of the cupula during short- and long-lasting inputs.

Nevertheless it should not be forgotten that the primary perception of movements in yaw direction happens via the visual channel.

2.1 Thresholds of Perception

Movements in space are recognized—apart from the visual channel—in an epicritic or mechanically receptive, haptic, but mainly vestibular way.

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 has difficulties with presenting

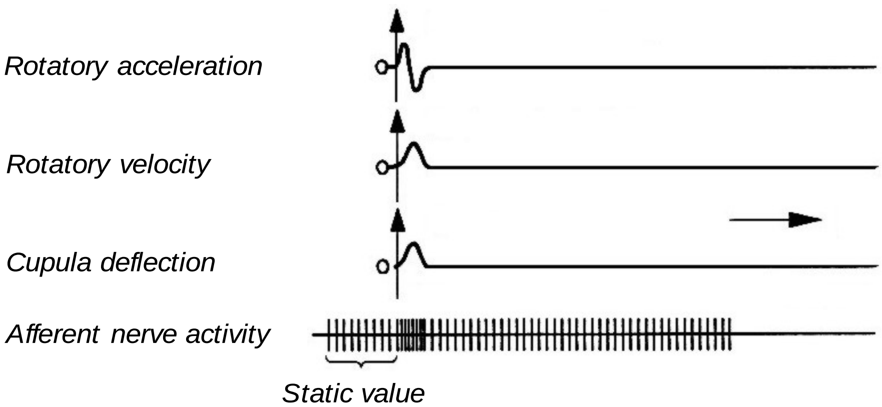


Fig. 4 Perception of rotational movements caused by short inputs.

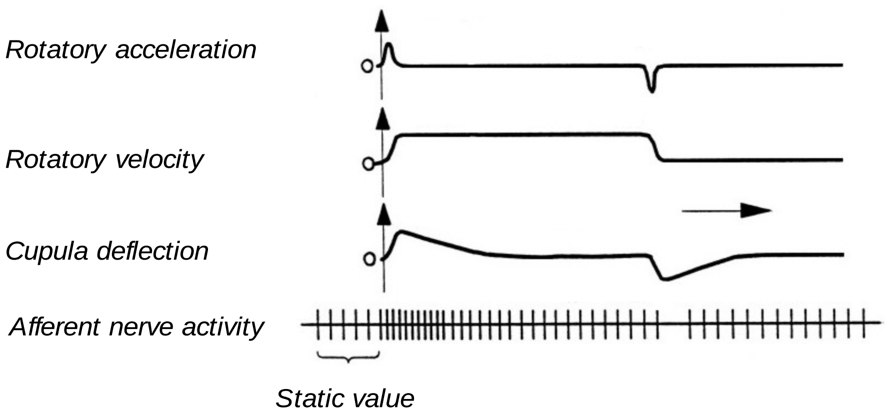


Fig. 5 Sensing of rotational movements caused by long-lasting inputs.

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.

Tests in a driving simulator made evident that the vestibular information affects the reaction-time of the driver up to 30% and has therefore positive influence on the stability of the control-loop driver-vehicle [3], which is shown by control theory with the criteria amplitude margin and phase margin [4].

For the layout of a moving base system for a driving simulator the thresholds of perception are of importance for presenting the individual vehicle movements especially considering the available workspace. On the one hand, only these accelerations have to be presented, which are noticeable by the driver of a vehicle, on the other hand, movements, which may give a false motion impression, should not be noticed by the driver.

The thresholds of perception can be determined by subjective ratings. A different way could also be an objective statement via the so-called nystagmus. The nystagmus is the coupling of the eye movement with the vestibular organ, which corrects the eye movement during head and vehicle movements.

In the existing literature a large number of values for thresholds of perception exist, which differ often considerably, see Table 1. This might be caused by different testing conditions and durations as well as the presentation of additional information to the test subject, which could lead to partly very different results. Furthermore it has to be taken into account that the perception of movements varies widely depending on the input frequency. It has also influence, whether the test subject exceeds the threshold of perception from the neutral position or whether he is moved from clearly noticeable movements to values below the threshold. Also the overlapping with other movements is of great interest for the perception of movements in a single direction [2, 5].

3. Presentation of Motion with Hexapod Systems

Hexapod systems have the advantage to move in all 6 DOF. Because of the limited space in sway, surge and yaw, accelerations are mainly simulated via tilting the cab.

Figs. 6 and 7 illustrate the motion of tilting systems by means of two examples for basic movements providing an acceleration impression during a braking maneuver based on traditional (classical) washout algorithms [6]. Fig. 6 shows a superimposed motion with a pivot in the area of the driver's head. The associated diagram on the right shows a typical run of the acceleration $a_{x,sens}$ perceived by the driver. The data have been taken from measurements at a truck driving simulator, where the driver's cab has been mounted on a Stewart-platform [7].

Fig. 7 indicates the influence of an excentric pivot during an angular movement. The motion system providing the data for the diagram has also been used for a truck driving simulator. In this example the

Table 1 Thresholds of perception.

Motion	Axis	Acceleration	Threshold band width	Threshold considered for moving base systems
Rotation	roll	$\ddot{\phi}$	0.1-8.2 deg/s^2	4-5 deg/s^2
	pitch	$\ddot{\vartheta}$	0.1-8.2 deg/s^2	4-5 deg/s^2
	yaw	$\ddot{\psi}$	0.035-6.0 deg/s^2	4-5 deg/s^2
Translation	vertical	a_z	0.05-0.5 m/s^2	0.18-0.2 m/s^2
	sway	a_y	0.01-0.2 m/s^2	0.18-0.2 m/s^2
	surge	a_x	0.002-0.2 m/s^2	0.18-0.2 m/s^2

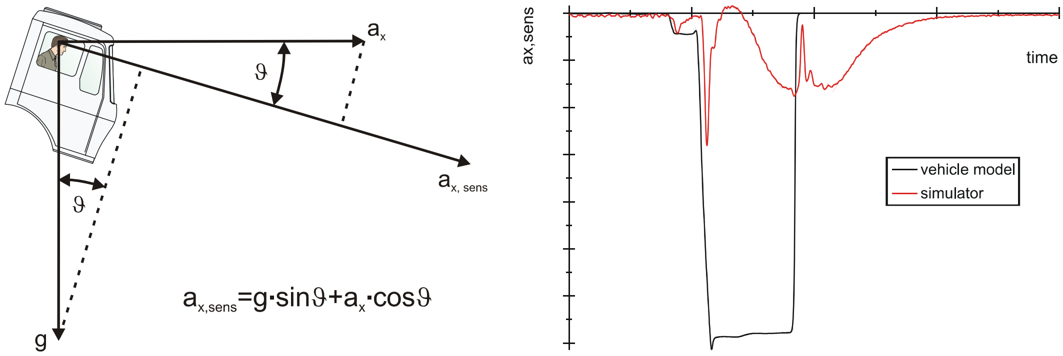


Fig. 6 Superposition of high and low frequent acceleration sections.

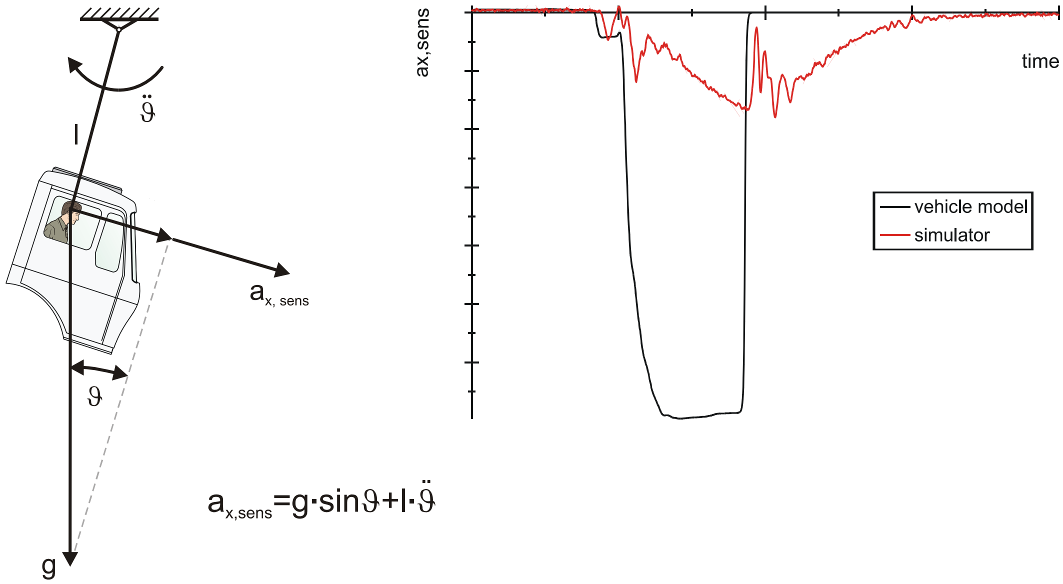


Fig. 7 Influence of excentric pivotal point.

motion system consisted of diagonally arranged ramps [7], which results in a non-typical pivot above the driver's head.

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 via tilting.

4. Expansion of Hexapod-Systems by Linear Degrees of Freedom

The component gravity is responsible for the drivers feeling of acceleration, see Fig. 6. Here it must be considered that the simulation of lateral accelerations by tilting works only up to about 25° (Aubert-effect), which corresponds to a value of 4 m/s². Higher inclination angles will be noticed by the driver. While the rotation in roll direction does indeed produce a lateral component of acceleration to a seated subject, a cue conflict may occur, when the subject senses the rotational aspect of the motion, which in this case is an artificiality. According to the literature the sensory threshold of rotation is about 4-5 deg/s², see Table 1. Taking this into account only a slow increase of accelerations by rotation is possible, see Fig. 8. That leads to the conclusion that fast reactions of the driver can only be simulated by transverse motion, if a sensation of a rotational movement shall not be noticeable.

In order to avoid these disadvantages the Institute

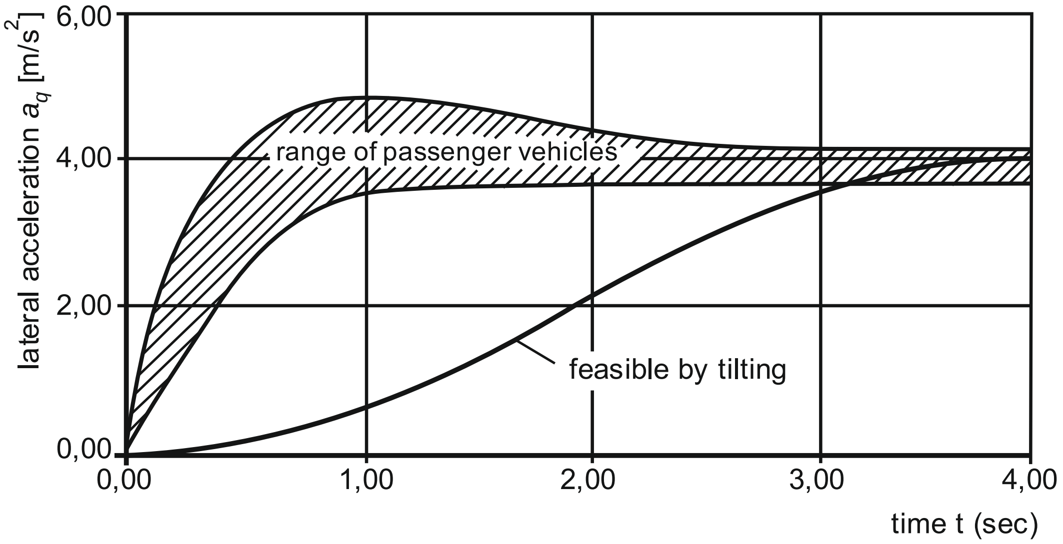


Fig. 8 Simulation of a step steering input considering the threshold of rotation.

of Automotive Engineering in Hamburg extended the existing hexapod-system, see Fig. 9, with an additional actuator in sway direction and made a concept for a sway acceleration system electrically driven by a linear motion system (see Fig. 10 [8]), which was presented in 2002 at the DSC Conference in Paris.

Nevertheless these abilities to present a more realistic feedback for the driver go along with much more needed workspace—maybe also kind of a trade-off.

Currently more and more driving simulators are built or upgraded with additional translatory motion abilities. To limit the complexity and the investment often only the sway direction is realized, see Fig. 11.

Most of them consist of hexapod systems with linear motion systems in X direction (e.g. Mercedes Benz Stuttgart, ika Aachen) or in XY-direction (e.g. FKFS Stuttgart).

5. Possibilities of Presenting Motion in the X-Y-Plane

Simulators often have problems with presenting several kinds of manoeuvres including for example an acceleration step (see Fig. 8), whose amplitude lasts for a longer time (full braking, step steering, etc.). One

Fig. 9 Expansion of the hexapod-system of the IFAS-simulator.

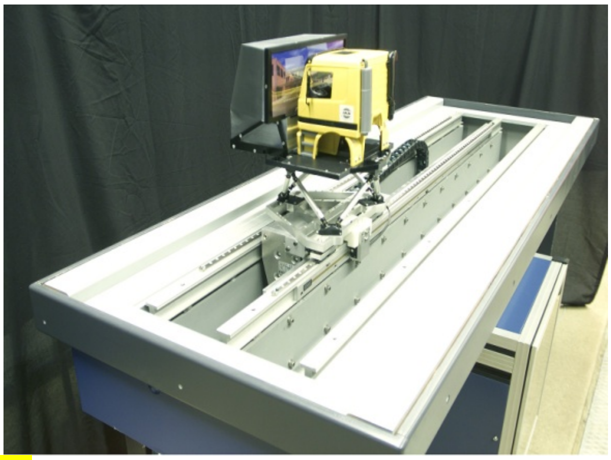


Fig. 10 Electrically driven linear motion system with a model of the 6-DOF IFAS-simulator (see also Fig. 9). Presented at the DSC Conference 2002 in Paris.

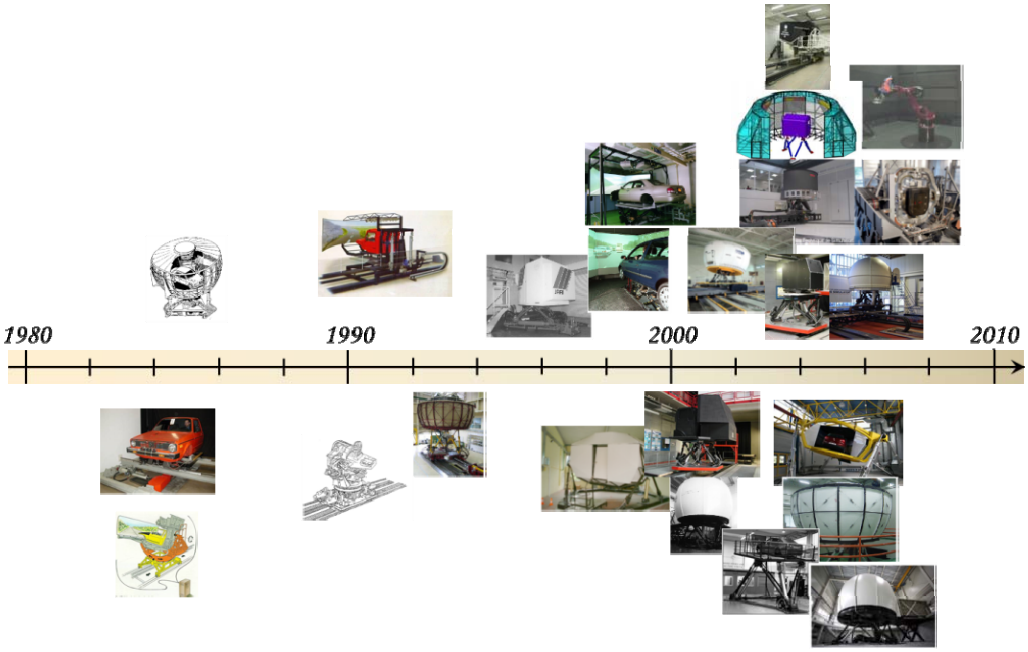
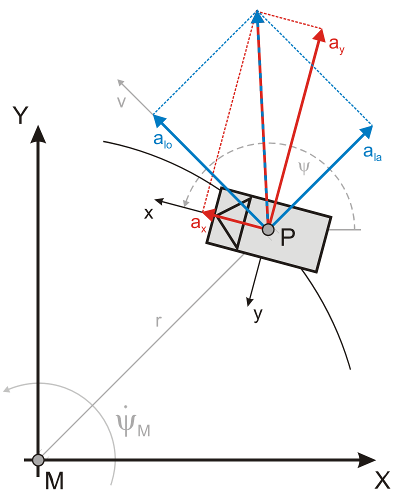


Fig. 11 Development of driving simulators [9].



Lateral acceleration:

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

Tangential velocity:

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

Resulting acceleration:

Fig. 12 Acceleration vectors at driver's cab.

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 approach of trying to abandon 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. Fig. 12 shows the superimposed and transformed acceleration vectors at a possible driver's cab in the x-y-plane.

5.1 The Sensation of Yaw-Movements

A human being perceives yaw movements in different ways. As already mentioned yaw velocities are mainly perceived visually, whereas the perception of yaw accelerations takes place in the vestibular organ (→ cupula, Fig. 3). 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 an over-critically damped torsion pendulum [6].

Using a motion platform in order to simulate lateral accelerations via centrifugal forces, it must be ensured that yaw movements, which deviate from the current driving condition, are not sensed by the driver in order to avoid nausea. Therefore tests were done to make basic research regarding this subject [10].

5.2 Experimental Setup and Test Program for Sensing Yaw Movements

To get more information about the perception or the possibilities to scale yaw movements first of all a 1-DOF-simulator has been built, see Fig. 13. It provides a fully equipped driving environment. Around the driver's seat, which is placed in the centre of rotation, the drive unit of the system is able to accelerate the cab with more than 1,000 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. Mounting the driver's seat out of the centre of rotation also lateral accelerations will take effect on the driver's feeling.

To get an idea about the possibilities of tricking the human beings perception a large test program has been developed, from which important parts are presented below. For analysing the perception of different kinds of angular movements, variously scaled vestibular information has been presented in different driving situations on virtual proving grounds, which have been created especially for this purpose.

Under consideration of the limitations given by the electric motor (performance data, frequency response, etc.) a characteristic diagram has been developed. It contains test points, which indicate the absolute presented acceleration in the first column ($\ddot{\psi}_{in} = 0 \text{ deg/s}^2$) and the ratio between the calculated ($\dot{\psi}_{in}$) and the presented ($\ddot{\psi}_{out}$) values of the yaw velocity and acceleration respectively in the other columns. All these tests have been repeated several times to firm the results statistically.

Table 2 shows main parts of this diagram with the calculated value resulting from the current vehicle dynamic state on the x-axis.

Here the following conditions have been taken into account:

- max. calculated yaw acceleration of $|\ddot{\psi}_{in}| = 12 \text{ deg/s}^2$;
- max. calculated lateral acceleration of ay = 8 m/s²;
- drive on clothoid shaped curves (clothoid angle τ = 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. Fig. 14 shows a vertex clothoid with a typical run of the yaw acceleration and the lateral acceleration.

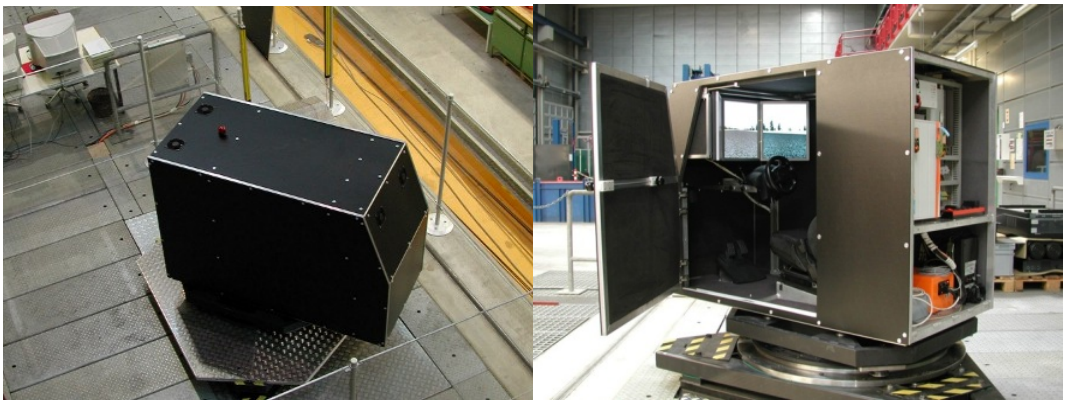


Fig. 13 1-DOF-system.

Table 2 Overview over test points.

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

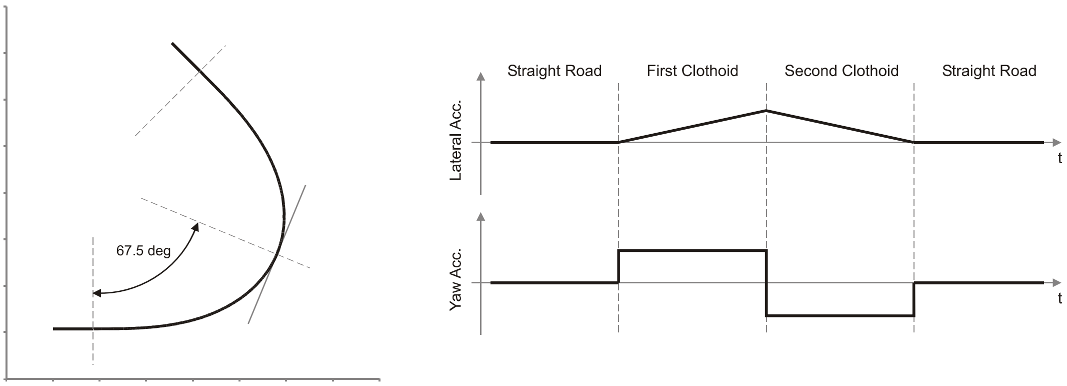


Fig. 14 Vertex clothoid.

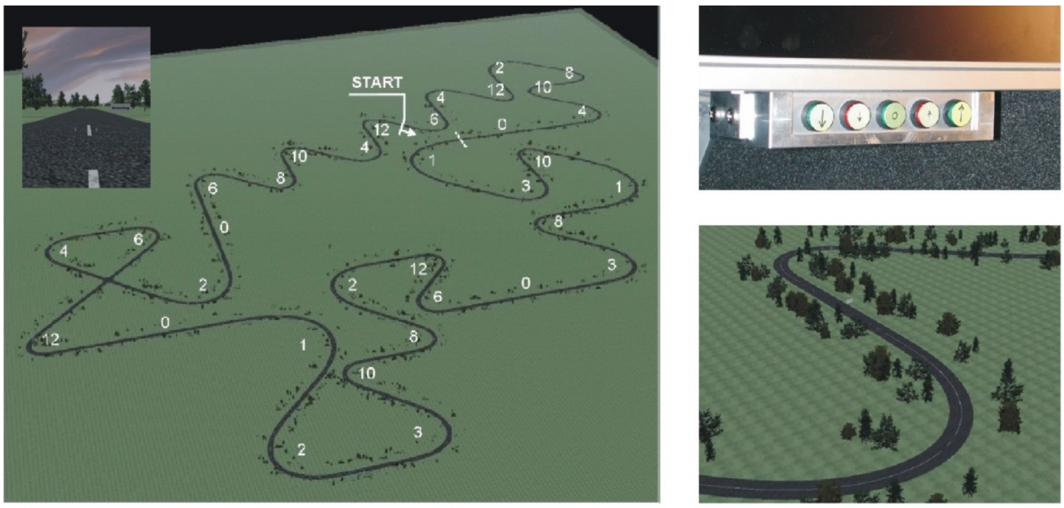


Fig. 15 Database with driver's view, zoom and pushbuttons.

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.

Fig. 15 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 2, 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 give an overview over the used database, indicate the absolute yaw acceleration when passing through the curve in the middle of the road.

The rating of the presented yaw movement has been made via pushbutton, see Fig. 15. Five categories have been distinguished, see Table 3. The number in the fourth column characterizes the category and has later been used for the analysis.

The individual scaling/offset-factors being adjusted for every curve have been chosen randomly to avoid systematic errors. Forty people had participated in this study, twenty-six everyday drivers and fourteen 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 previously 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. Fig. 16 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 Fig. 15: “3” and “10”).

It is obvious that the ideal run of the curves (see Fig. 14) is nearly not reachable when the driver is driving on his own. This also underlines the importance of the already mentioned way of driving.

5.3 Test Results

Fig. 17 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 3).

Table 3 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

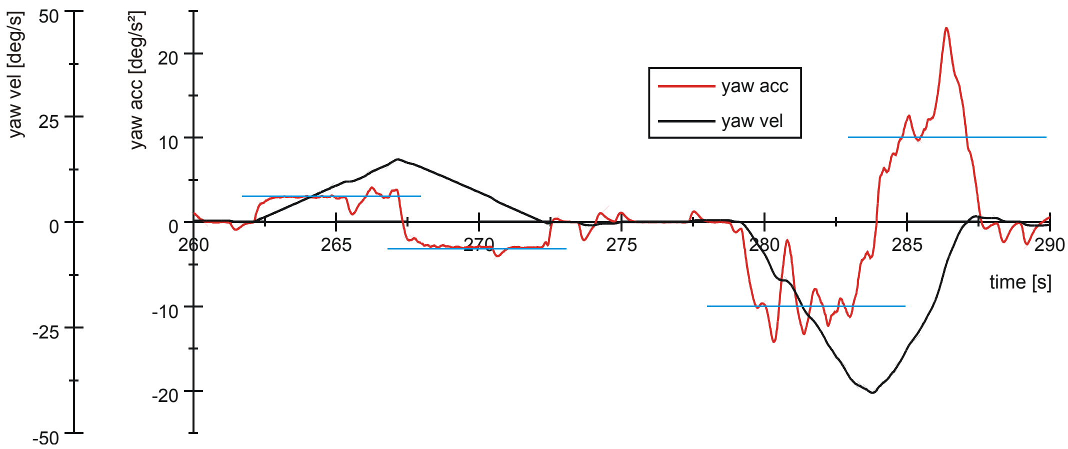


Fig. 16 Drive of a test driver through two vertex clothoids.

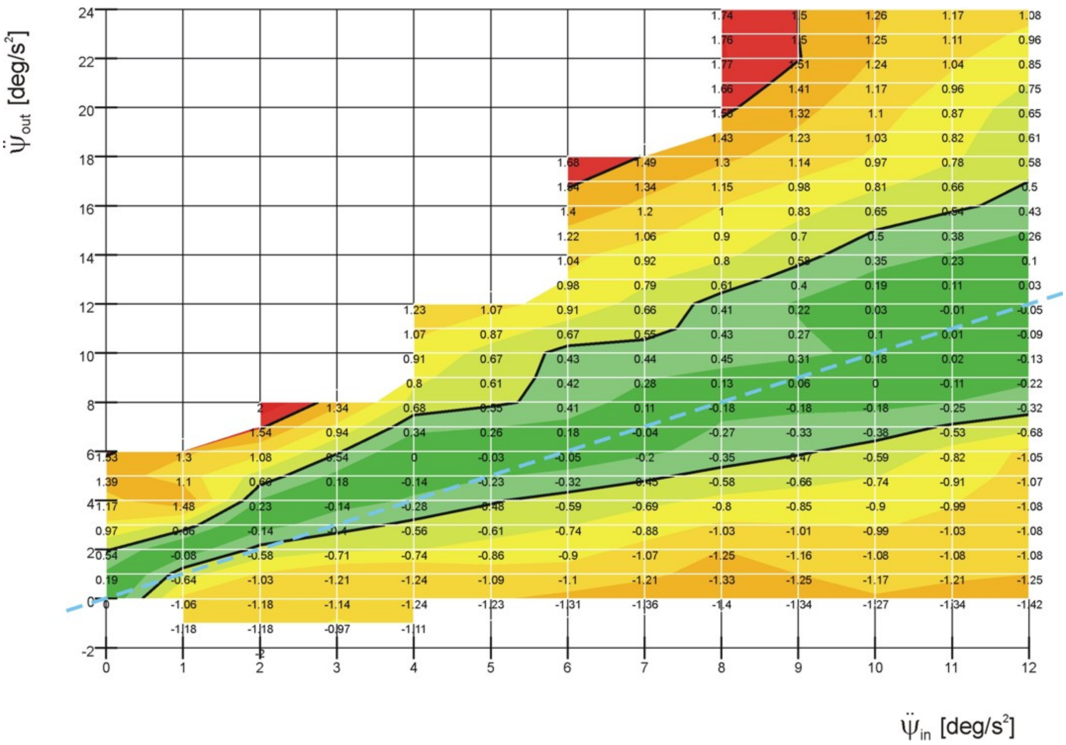


Fig. 17 Averaged ratings of all participants.

The blue dashed line indicates the points, where the yaw acceleration is presented true to scale.

First of all it is visible 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 a very 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.

This test has been carried out with everyday drivers and been repeated at a different date with professional test drivers. Here it is observable that for the professional drivers the corridor is narrower and a little displaced to lower acceptance limits. But on the whole the results have been nearly the same.

To consider the distribution of the results confidence intervals have been calculated for every test point. For this purpose 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 Fig. 18 shows possible offset/scaling factors versus the input acceleration for a probability value of 0.1%.

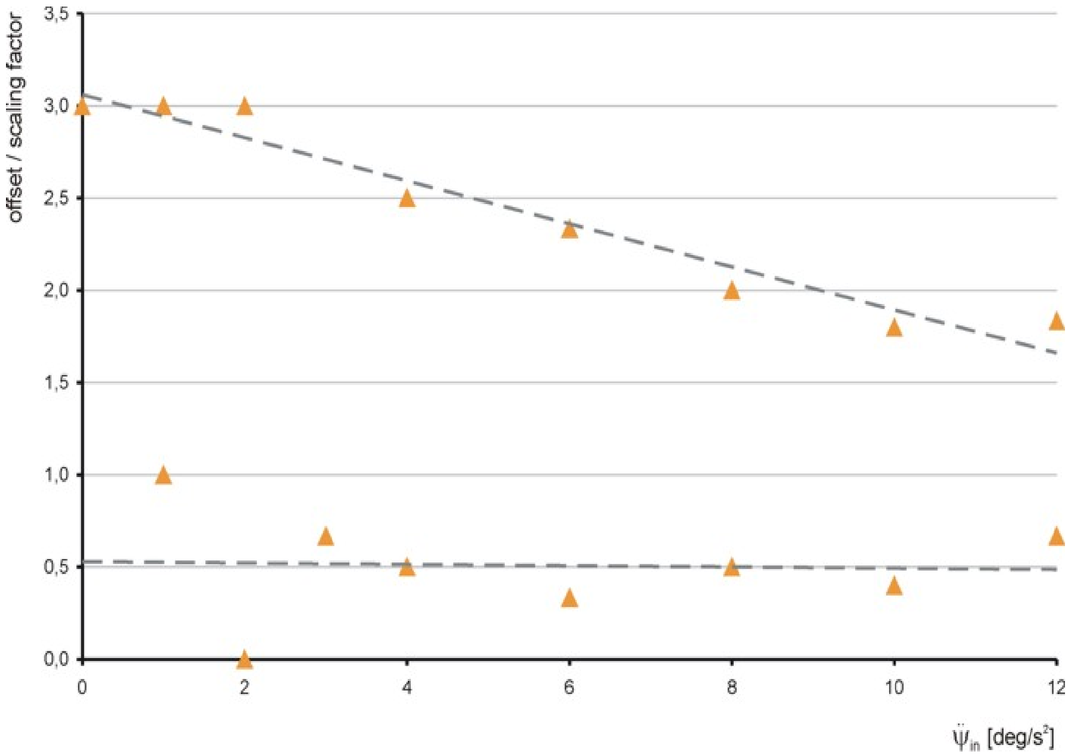


Fig. 18 Acceptable offset/scaling factors.

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 manoeuvres, 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 [11]. This is the most important mechanical control variable when driving a vehicle and may therefore raise the acceptable yaw rates. When using a motion platform for simulating lateral accelerations by rotating it must be ensured that the scaled yaw movements have to be within acceptable areas. This underlines the importance of the results for an adequate MDA (motion drive algorithm) for this kind of motion presentation.

6. Superposition of Yaw and Lateral Accelerations

The idea of an extensive abandonment of angular movements could result in the use of centrifugal forces for presenting sustained accelerations. These forces can be partly used to reduce the workspace needed when presenting all movements on ground level with a special kind of vehicle. Assuming that it is possible to present all other accelerations true to scale the yaw motion is the only relevant one, which has to deviate more or less from reality. The previous tests made evident that there is a certain area, where a divergent scaling of the yaw motion is possible. Now the question is, how the results shown in Fig. 17 are influenced by the superposition of sway accelerations.

Based on the presented results and considering that sway accelerations occur with nearly every yaw movement, the assumption was made that a combination with sustained sway accelerations via tilting will probably raise the acceptable yaw rates. This is also underlined by other tests, which have shown that the superposition of motion raises the thresholds of perception [2].

The problem of not yet having the chance to present sustained motion impressions in sway direction in the desired x-y-plane led to the idea of presenting these accelerations by tilting the driver's cab with a hexapod-system. After combining the 1-DOF-simulator with an already existing hexapod-system, the originally classical MDA had to be modified so that unlimited yaw motions are presented accordingly.

Fig. 19 shows the original driving simulator MARS (modular automotive research simulator) on the left based on a hexapod motion system and an additional 7th DOF for movements in lateral direction. In the middle we can see the already presented stand-alone 1-DOF-system and on the right the combination of both to an 8-DOF-motion system.

To give a better idea of how scaled yaw and sway motions work together, Fig. 20 visualizes the angular positions of the simulator at different points on the curve, while a test person drives a 180-degrees vertex clothoid with double yaw rate.

First preliminary tests have shown that a superposition with an acceleration impression in sway presented via tilting 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.

6.1 Test Program and Results

The first test presented deals with the influence of the exposure time when driving through different curved vertex clothoids, which are characterised by the maximum clothoid angle τ_{max} starting from the beginning of the curve to its vertex. Compared to Ref. [10] a modified database was used involving a test series with 26 test persons. Fig. 21 shows a section of the driver's view, Fig. 22 a diagram, in which the selected clothoids used in Ref. [10] (blue rhombus) and the additional ones in the current test series (green square and red triangle) can be seen. These test points result from considerations out of vehicle dynamics and road construction. Also the already mentioned kinematic and dynamic limits of the motion system partly reduce the test area significantly.

The blue dashed line indicates the points, where the yaw acceleration is presented true to scale.

Fig. 23 shows the results based on rated test points for both clothoid angles studied. The numbers inside the coloured surface indicate the mean rating, which is also illustrated by the nuance of the main colours used as given in Table 3. The points in the diagrams, which were not directly rated by the test persons (not indicated) but are useful to obtain a closed surface area, were non-linearly interpolated based on the surrounding points. Also the same rating categories as indicated in Table 3 have been applied.

Compared to the expected influence of the large time constants of the semi-circular channels (overview in Ref. [12]) an relevant influence of the exposure time for practical use cannot be observed under these test conditions. It is evident that it was not possible to

Fig. 19 Driving simulators in 7-, 1- and 8-DOF configuration.

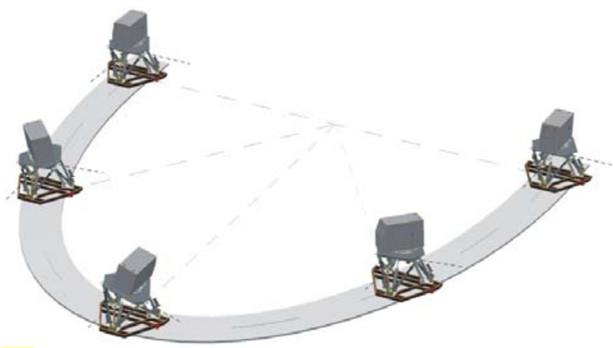


Fig. 20 Superimposed motion with double yaw rate.

Fig. 21 Driver's view.

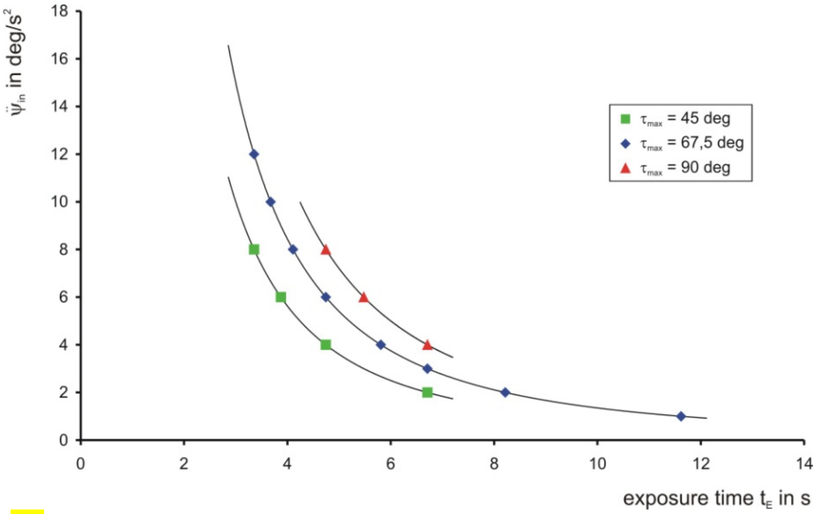


Fig. 22 Selected test points.

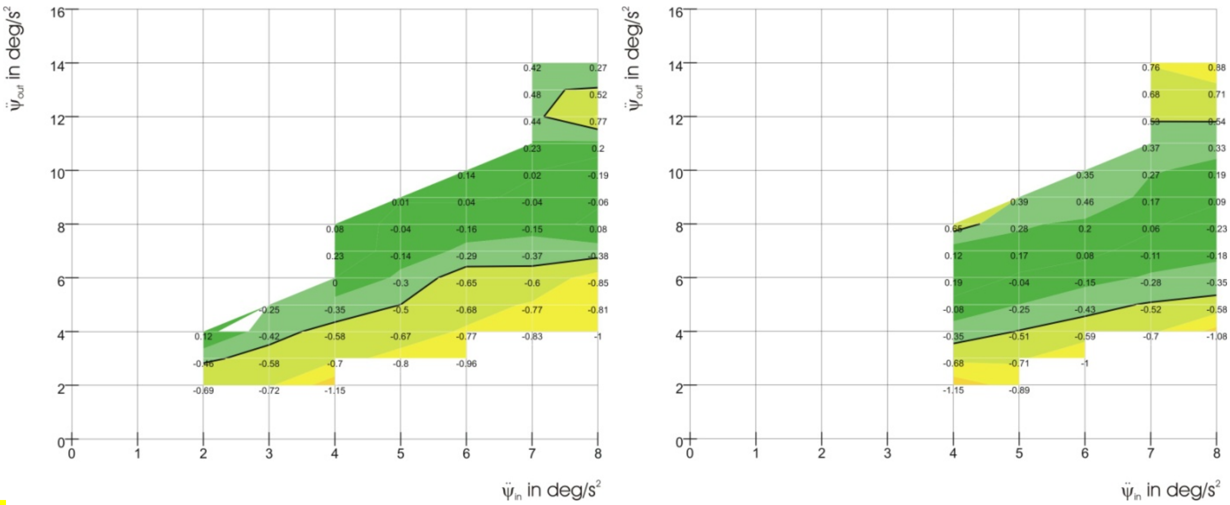


Fig. 23 Factor $a_y = 0$, $\tau_{max} = 45$ deg (left) and $\tau_{max} = 90$ deg (right).

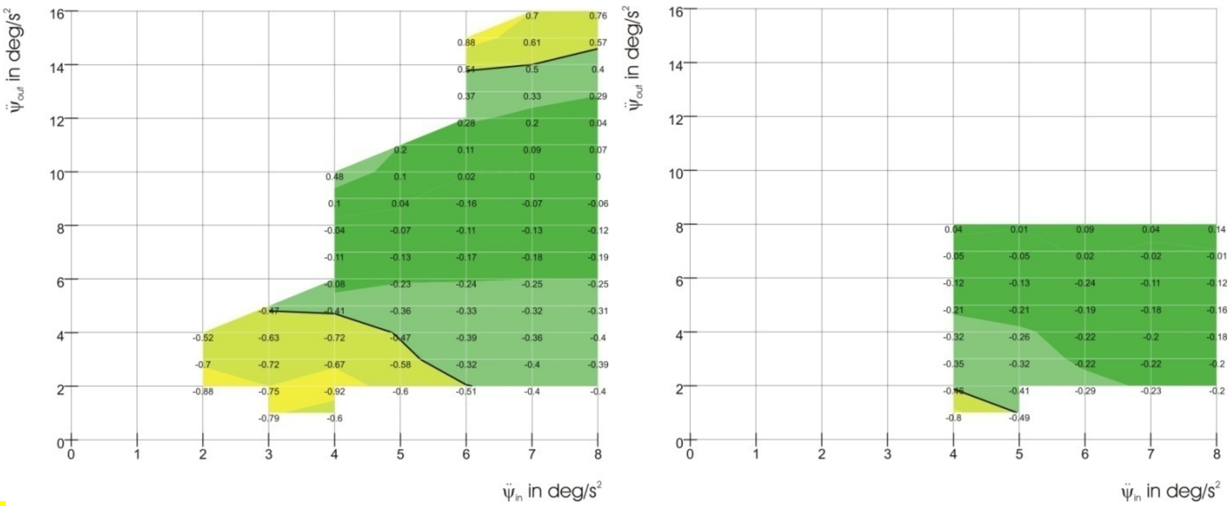


Fig. 24 Factor $a_y = 0.2$, $\tau_{max} = 45$ deg (left) and $\tau_{max} = 90$ deg (right).

find limits of acceptance in all areas, but even without taking a deeper look at confidence intervals, basic tendencies are noticeable.

Afterwards the test was repeated under nearly the same conditions but with 20% sway acceleration. This investigation with 25 test persons showed that this additional information increased the acceptable yaw rates significantly, see Fig. 24.

Not only the upper possible factor increases, but the field in the lower area also expands. As already seen before without sway accelerations, the omission of yaw movements is to some extent still perceived by the test person even with 20% lateral acceleration.

Subsequently a last test within this series was carried out, in which the sway acceleration was represented true to scale. Because of the restricted abilities of the motion system, the curves in the database used had to be limited to an absolute yaw acceleration of $\ddot{\psi}_{in} = 3 \text{ deg/ } s^2$, a clothoid angle of τ_{max} = 30 deg and a driving speed of v = 30 km/h. Here the quality of the interaction of the hexapod and the yaw table is particularly important to avoid potential time differences and a subsequent sensation of longitudinal motion. Figs. 25 and 26 show the database and the rating of the 25 participating test persons.

As expected, this configuration again led to higher acceptable yaw rates and confirms the initial statement that superimposed cues in sway raise the already existing range additionally.

Based on all previous results the MDA for a moving-base system, whose kinematics allow the involvement of yaw movements into the presentation

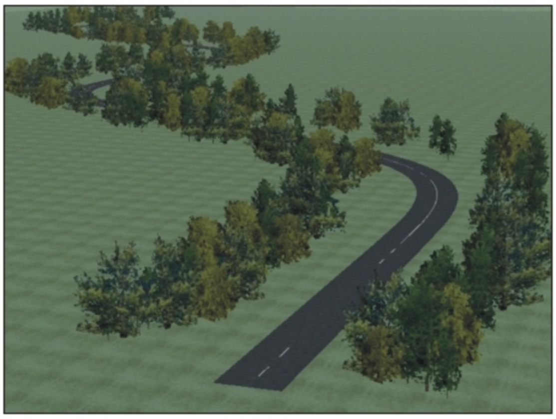


Fig. 25 Database.

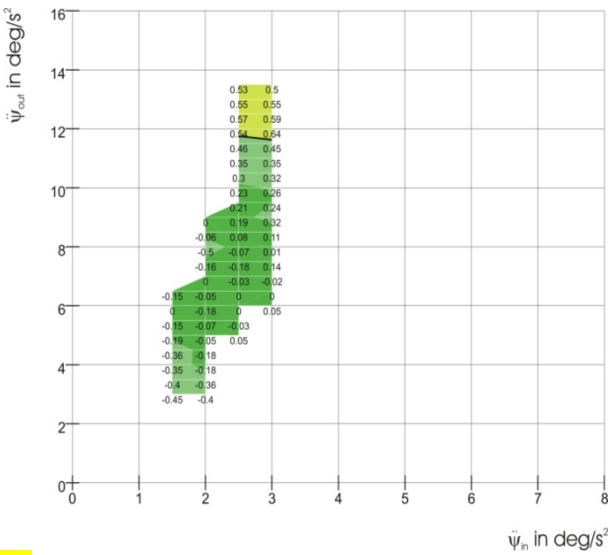


Fig. 26 Result for factor a_y = 1, τ_{max} = 30 deg.

Table 4 Pros and cons of different motion systems.

	6-DOF with hexapod	1-/2-DOF linear motion	1-DOF rot motion
Pro	compact system	large workspace	long lasting accelerations in yaw sway and surge
	presentation of translatory and rotatory movements in all 6 DOF possible	realistic rise of translatory accelerations	1ong exposure time possible
	realistic presentation of inclination angles	when engine strong enough realistic but short exposure time	
Contra	only slow motions (except for heave) meaningful	large wash-out necessary	yaw-scaling within the sensory limits necessary
	step inputs mostly not realistic	cost intensive	vehicle useful for change over between different driving conditions

of translational accelerations, has the possibility to operate with scaled yaw rates. Depending on the scaling of the sway acceleration a yaw factor of more than 4 seems to be imaginable based on the previous findings.

7. Conclusions

This paper deals with the possibility of simulating accelerations with driving simulators by tilting, linear and rotatory motions. Table 4 gives an overview of advantages and disadvantages of motion presentation using different degrees of freedom.

With hexapod systems all movements in 6 DOF can be realized. But those systems are very limited in sway, surge and yaw direction. In order to compensate these disadvantages hexapod systems can be extended by linear motion components, which have no rotatory capabilities when used stand-alone. Rotatory movements however can be realised via a turntable or a special vehicle.

The basic principles of a rotating component considering the technical design and the physiological and biometric effects have been the main topic in this paper. It has turned out that there is an area, which allows a certain yaw scaling depending on its superposition with sway accelerations. These results allow movements in the x-y-plane consisting of special moving trajectories using in particular scaled/offset yaw movements. This can be realised with a modified layout of the well-known components of motion systems but maybe also with a special vehicle. However, the need of certain degrees of freedom with certain capabilities for motion presentation hardly depends on the later field of application.

Using a motion platform in order to simulate lateral accelerations via centrifugal forces, it must be ensured that yaw movements, which deviate from the current driving condition, are not sensed by the driver in order to avoid nausea. Therefore tests were done to make basic research regarding this subject [10].

To get an idea about the possibilities of tricking the human beings perception a large test program has been developed, from which important parts have been presented above. For analysing the perception of different kinds of angular movements, variously scaled vestibular information has been presented in different driving situations on virtual proving grounds, which have been created especially for this purpose. The tests have shown promising results, which indicate that it could be worth getting on with this idea of motion presentation.

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