



# Towards Mission Readiness – Applying the Objective Motion Cueing Test to the Apparent Vertical Filter

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Flight training simulators have a limited capability to replicate aircraft motion cues because the space envelope of current motion systems impedes a better fidelity and urges the user to make sometimes painful compromises. Therefore, it is all the more important to use the given space envelope as well as possible. But this trivial consideration yields an answer to the question what “good” means and therefore what strategy shall to be pursued by a control algorithm. For the Apparent Vertical Filter (AVF) this means that the amount and direction of the force combined with the corresponding rotational velocity shall be met as long as the given space envelope allows that approach. If this is not possible anymore the direction of the specific force shall be reproduced correctly. Only if both, the rotational and the translational cueing cannot be achieved a decision must be made. This is the case e.g. for the side force during a taxi turn on ground. During such maneuvers a compromise needs to be found between a correct specific force and a limited rotational velocity of the simulator. Within this paper the working principle of the Apparent Vertical Filter will be discussed for a taxi turn on ground maneuver. Furthermore, it will give a general overview of the AVF response to lateral maneuvers in general. Finally, it presents the results for the lateral tests of the Objective Motion Cueing Test (OMCT) showing that, in general, the AVF is able to meet the requirements of the test.

## I. Nomenclature

A/C	Aircraft
AVF	Apparent Vertical Filter
$C$	Centrifugal force
CWA	Classical Washout Filter
$\vec{f}_{aa}$	Specific force vector of washout filter input signal
$f_{aa,x}$	Specific force in surge
$f_{aa,y}$	Specific force in sway
$f_{aa,z}$	Specific force in heave
$G$	Gravity force
$g$	Earth acceleration
$\vec{g}_I, \vec{g}_S$	Earth acceleration vector in earth and simulator fixed frame
$\vec{M}_{SI}$	Transformation matrix earth to simulator fixed frame
PA	Pilots eyepoint position in the aircraft cockpit
$\vec{T}_S$	Transformation matrix simulator to earth fixed frame for attitude angles
$n$	Load factor
$p$	Aircraft roll rate
$q$	Aircraft pitch rate
$r$	Aircraft yaw rate
$t$	Time
$\vec{x}_S$	Vector of commanded translational position of motion system
$\ddot{x}$	Acceleration in surge (longitudinal)
$\ddot{y}$	Acceleration in sway (lateral)
$\ddot{y}_S$	Commanded acceleration in sway (lateral) of motion system
$\ddot{z}$	Acceleration in heave (vertical)
$\vec{\beta}_S$	Vector of commanded angular attitude of motion system

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$\varphi_\omega$	Lateral apparent vertical angle perceived by the pilot due to roll angle
$\varphi_f$	Lateral apparent vertical angle perceived by the pilot due to specific side force
$\theta$	Aircraft pitch angle $\phi$ Aircraft roll angle
$\phi_S$	Commanded roll angle of motion system
$\vec{\omega}_{aa}$	Angular rate vector of washout filter input signal
$\omega_{aa,x}$	Roll rate of washout filter input signal
$\omega_{aa,y}$	Pitch rate of washout filter input signal
$\omega_{aa,z}$	Yaw rate of washout filter input signal

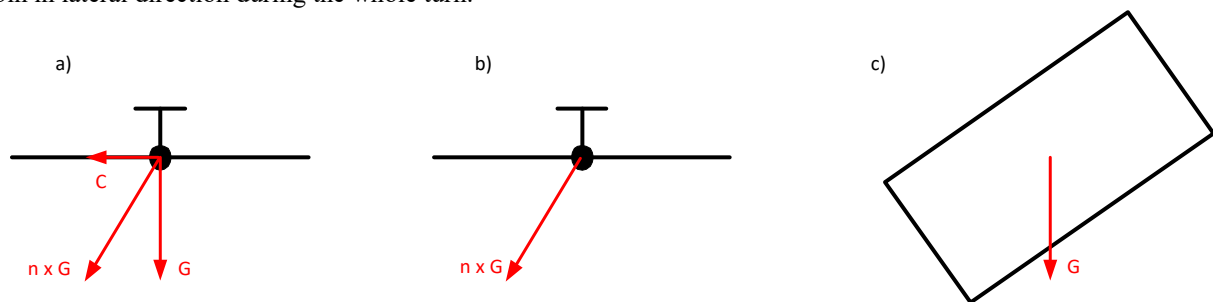
## II. Introduction

More than ninety years after Edwin A. Link invented the ‘‘Pilot Maker’’ [1, 2] the challenge to supply pilots with the best possible motion cues in a training simulator still remains. Thus, it is not surprising that the pros and cons of motion cues are widely discussed because the operating costs they entail [3, 4] need to be justified in an ongoing discussion about the transfer-of-training value of motion systems [5, 6]. Furthermore, pilots still feel interfering forces resulting from the fact that reaction forces, e. g. the centrifugal force during coordinated turns cannot be replicated due to the limited envelope space that is available for motion systems [7]. Summarizing all arguments above, it can be said that even though objective evaluation methods are to be discussed further, it is generally accepted that efforts have to be made to improve subjective motion cueing [8]. One current approach is the Lateral Motion Maneuver (LM2) filter [9, 10], which is able to compensate for some of the adverse effects of lateral maneuvers but is not valid for longitudinal accelerations that appear for example during take-off runs, climb and descent maneuvers. Another one is the Apparent Vertical Filter developed by DLR [11] which addresses some of these topics.

In general, cueing algorithms assume that pilots perceive movements as translational accelerations and rotational velocities resulting in two input signals [12], the rotational velocity and the translational acceleration. Taking this into account, one can distinguish three cases for lateral maneuvers:

- The coordinated turn characterized by a roll velocity with no lateral force as discussed in Ref. [13]
- The steady side slip with both, a roll attitude resulting in a corresponding lateral force, whose counterpart of a car running on a lateral slope is given in Ref. [14]
- The case of a lateral force without a roll attitude as a result of a turn on ground while taxiing which is discussed below.

In this paper a taxi turn on ground shall be defined as a turn without any roll attitude where the centrifugal force induces a side force that is felt by the pilot in the (aircraft) cockpit (see **Fig. 1** (a)). As a consequence, the apparent vertical from the pilot’s perspective diverts from the vertical axis of the cockpit as given in **Fig. 1** (b). It is obvious that the lateral side force cannot be replicated in the simulator cabin likewise due to the fact that it is neither possible to induce another external force in addition to gravity (e.g. centrifugal force) nor to accelerate the cabin in lateral direction during the whole turn.



**Fig. 1** Forces appearing during a taxi turn on ground in an aircraft in the earth fixed frame (a), how they are sensed in the aircraft in the body-fixed frame (b) and what can be achieved in a simulator cabin in cabin-fixed coordinates (c).

A pure lateral force will be reproduced by rolling the simulator cabin which leads to a major difference between the aircraft and the simulator cockpit movement (see **Fig. 1** (c)). The problem is that rolling the simulator cabin will induce roll cues that, if too fast, could be felt by the pilot and, if too slow, results in a huge time lag of the lateral force. Unfortunately, both effects can only be balanced for short and aggressive (e. g. engine fail during take-off) and long lasting smooth (e. g. taxiing slowly a wide turn) curves. For all other cases like normal curves on ground or rolling-off the runway with high-speed a trade-off needs to be made dependent on subjective preferences of the simulator validation crew.

## III. General Characteristics of a Taxi Turn on Ground

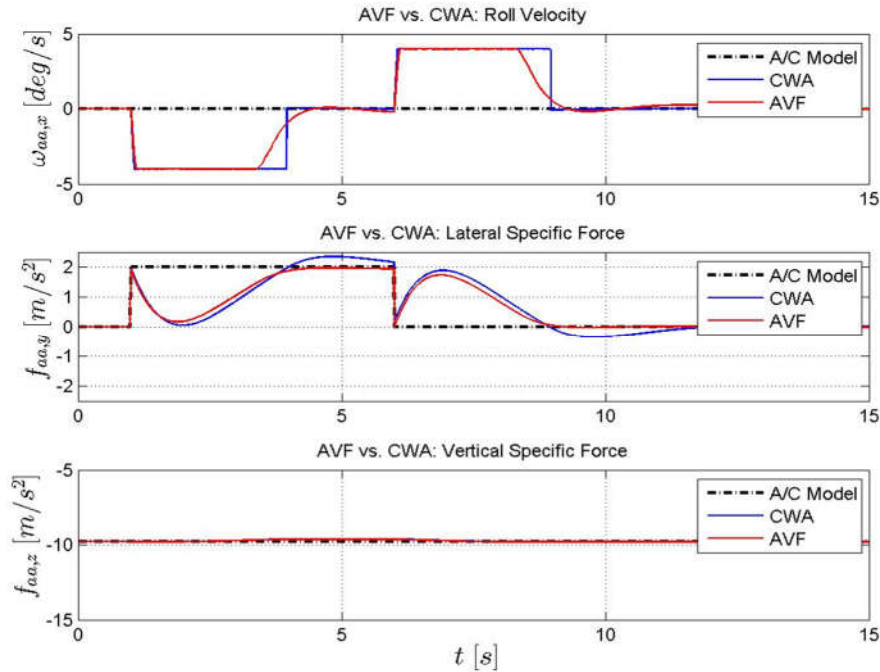
A taxi turn on ground within this context describes a lateral aircraft maneuver. At the beginning the aircraft is moving unaccelerated and straight. By deflecting the nose wheel a turn is induced while a side force can be

observed without any roll attitude. When reaching a certain heading the turn will be stopped by releasing the nose wheel control. During the turn the resultant of the centrifugal and gravitational forces will lead to an apparent vertical force that diverts from the vertical axis of the aircraft cabin during the maneuver.

The corresponding input signals for a motion control algorithm like the Classical Washout Filter (CWA) for a taxi turn may be idealized in a way shown by the black line-dotted graph in **Fig. 2**. The lateral specific force is a step input signal of  $2 \text{ m/s}^2$  for 5 seconds. A side force of this size may be seen as typical for an aircraft like an Airbus A320 or Boeing B737 size. Meanwhile the roll attitude of the aircraft remains zero resulting in a roll rate that remains at  $0^\circ/\text{s}$  for the entire maneuver. The vertical specific force matches the normal gravitational acceleration. Subsequently, the specific force and the roll rate input signals are defined by

$$\vec{f}_{aa} = \begin{pmatrix} f_{aa,x} \\ f_{aa,y} \\ f_{aa,z} \end{pmatrix} = \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix}_{PA} - \begin{pmatrix} -\sin(\theta) \\ \sin(\phi) \cdot \cos(\theta) \\ \cos(\phi) \cdot \cos(\theta) \end{pmatrix} \cdot g = \begin{cases} \begin{pmatrix} 0 \\ 2 \text{ m/s}^2 \\ -g \end{pmatrix} & \text{for } t=[1\text{s}..6\text{s}] \\ \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} & \text{else} \end{cases} \quad (1)$$

$$\vec{\omega}_{aa} = \begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{pmatrix} \omega_{aa,x} \\ \omega_{aa,y} \\ \omega_{aa,z} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad (2)$$



**Fig. 2** Filter input signals and the response of a Classical Washout Filter (CWA) as well as for an Apparent Vertical Filter for an idealized taxi turn on ground.

### A. System Response of a CWA to a Taxi Turn on Ground

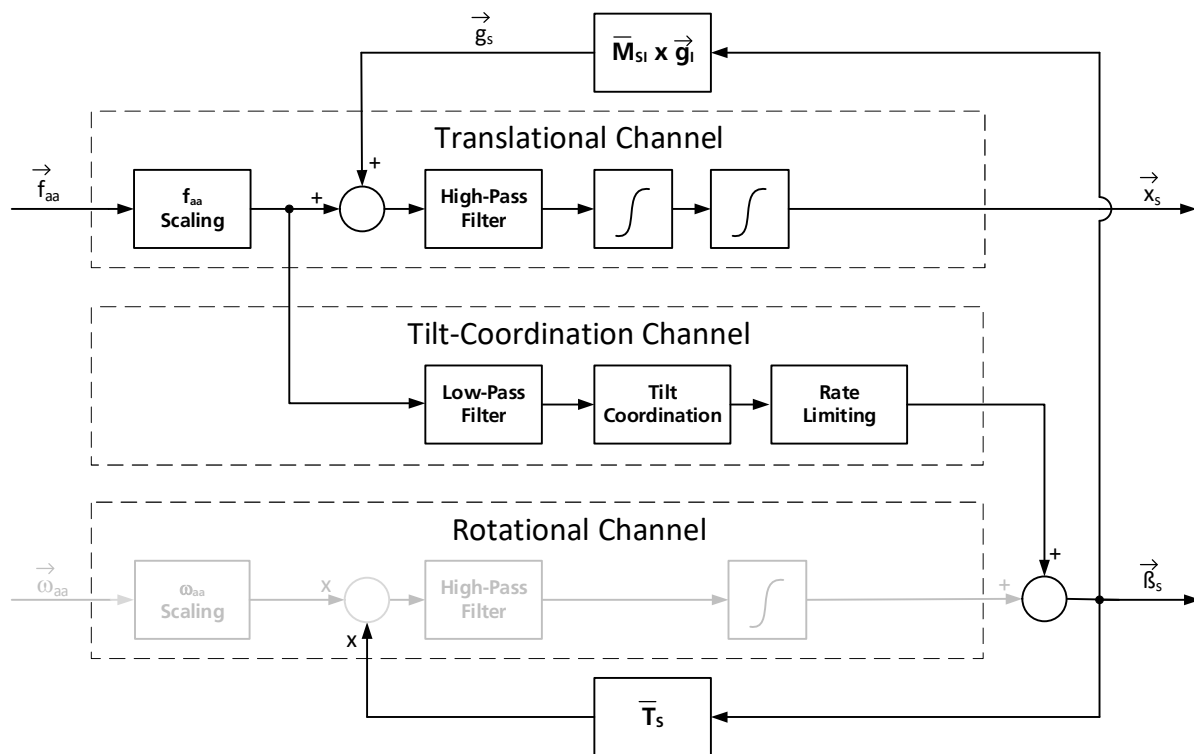
At least since the first CWA research report was published by the University of Toronto [12], the CWA has become the most popular and probably the best analyzed motion drive algorithm in use in flight training simulators. And even though today a number of derivatives of the published CWA are in use, all of them are based upon the algorithm presented in Ref. [12]. For that reason, this algorithm is used as a reference algorithm for the research presented in this paper. The response to the input signals defined above will be discussed using the CWA structure as shown in **Fig. 3**, where the parts which are not relevant for the current maneuver are greyed out.

The output signals are the position vector and the attitude vector of the aircraft at the pilot's eyepoint. Due to the high-pass filter of the translational channel short term accelerations will lead to translational accelerations of the motion system, while long term signals will lead to attitude angles using the low-pass filters of the tilt-coordination channel. The short-term rotational rate input signals, that pass the high-pass filter of the rotational channel, will lead to short-term attitude angles of the simulator cockpit, while long term signals will be filtered out. For the idealized taxi turn on ground it is assumed that the longitudinal specific force as well as the pitch and

the roll attitude can be neglected. Therefore, the rotational channel contributes nothing to the reaction of the simulator cabin.

In **Fig. 3** all parts that are either not relevant for lateral forces or negligible due to the input signals as defined above for the taxi turn are greyed out. The high-pass filtered parts of the translational input signal will be integrated twice to find the translational position. As the high-pass filter is of third order a constant non-zero input signal will lead to a movement of the cabin ending up at the neutral position. The low-frequent part of the translational input signal will be transformed into a rotational simulator cabin attitude using the tilt-coordination module. The tilt-coordination module calculates the g-induced forces due to the cabin roll in the lateral and cabin pitch in the longitudinal direction. Whereas a roll velocity may be noticed in a simulator but not in an aircraft a rate limiting function limits the angular rate in a way that, ideally, the simulator pilot will not sense it. Because the output of the rotational channel is zero during the taxi turn on ground, only the roll angle given by the tilt-coordination channel results in the commanded angular position the simulator cabin will go for.

In a feedback channel the commanded cabin attitude is used to transform the gravity vector into the simulator fixed frame. The result is added to the translational channel input signal. During a steady side-slip maneuver as given in [14] where the aircraft roll attitude shall lead to a simulator roll attitude this function prevents the translational channel from producing a translational acceleration. As discussed in [13], in case of a coordinated turn this compensation shall suppress lateral forces due to a simulator cabin roll attitude at the start of the turn by accelerating the cabin laterally. In summary this feedback loop shall compensate unwanted lateral specific forces.



**Fig. 3** Classical washout filter algorithm processing an idealized taxi turn on ground input signal.

Within the context of a taxi turn on ground this feedback loop, in theory, results in an unprecise specific side force in the simulator. For further explanation an unlimited space envelope shall be assumed for a short mind experiment. In this experiment a complementary couple of filters in the translational and the tilt-coordination channel would lead to a correct simulation of the lateral specific force. Because of the feedback loop a lateral acceleration signal will increase the high-pass filtered input signal within the translational channel. This makes the idea of the complementary filter ineffective by disturbing the ideal response. In reality, with different filter orders in both channels and having to regard the space envelope, this effect is hardly noticeable for the beginning of the maneuver because the tilt-coordination channel is rate-limited for physiological reasons and the effect itself is small compared to the input signal.

After the maneuver ended this effect appears and has to be considered differently. A small, maybe disturbing effect can be seen when long after the end of the turn a side force to the opposite direction occurs. This, if noticed by the pilot, is a false cue which may induce a control input to answer an acceleration that does not exist.

The blue line in **Fig. 2** shows the response of a classical washout filter algorithm with respect to a taxi turn on ground. The filter tuning corresponds to a setting of a comparable filter used in an approved Boeing B737 flight training simulator operated by a major air transport company. As expected the lateral specific force input signal

results in a low-pass filter output for the roll velocity and a high-pass filter response for the lateral acceleration. The second graph shows the resulting lateral specific force in the simulator cabin as a sum of both the lateral acceleration and the roll attitude of the simulator cabin. The specific side force shows a quick response due to the output of the high-pass filtered translational channel. While the share of translational acceleration decreases short after the start of the maneuver, the tilt-coordination channel driven output increases constantly over time. After stopping the taxi turn the response of the CWA is the other way around. Because the vertical input signal is constant the vertical specific force in the simulator stays at  $-g$  during the observation period.

### B. System Response of an AVF to a Taxi Turn on Ground

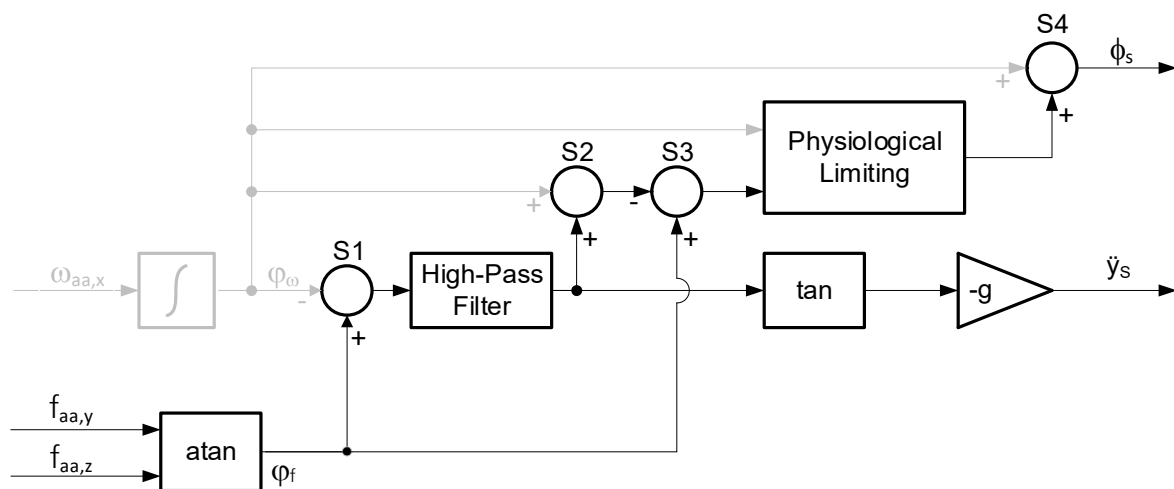
The main idea of the Apparent Vertical Filter is to represent the specific forces in the simulator with respect to the perceived apparent vertical angle rather than the correct quantity. Mathematically spoken, the orientation of the force vector should be correct as far as possible, while the length of the vector is to be adapted to the technical constraints of the motion system. This is achieved by comparing the current aircraft attitude angles with the current specific force vector cued in the cockpit. It should be noted that a single translational acceleration as well as a single change of the angular attitude leads to a change of the cued apparent vertical angle different from normal gravity. As a consequence, both, single specific forces and single angular attitudes can be expressed as a change of the apparent vertical angle.

**Fig. 4** shows the principle of the apparent vertical filter for the processing of lateral maneuver input data. Any lateral maneuver of an aircraft is characterized by a specific apparent vertical angle induced by a roll rate, a specific side force in relation to gravity or of both. The apparent vertical angle due to the aircraft angular attitude can be found by integrating the roll rate

$$\varphi_{\omega} = \int \omega_{aa,x} \quad (3)$$

while the apparent vertical angle due to a lateral specific force is given by

$$\varphi_f = \text{atan}\left(\frac{f_{aa,y}}{f_{aa,z}}\right) \quad (4)$$



**Fig. 4** Lateral Channel of an Apparent Vertical Filter according to Ref. [10].

For a taxi turn on ground the apparent vertical angle due to a roll rate is negligible. For the lateral specific force, it matches the angle between the normal gravity vector and the sum of the specific forces in lateral and vertical direction. Concerning the sum S1, the latter one therefore remains unchanged and will be high-pass filtered. The resulting signal, on one hand, is directly transferred to a corresponding lateral acceleration output. On the other hand, via sum S2, it is subtracted from the unfiltered signal at sum S3 leaving a low-pass filtered signal of the apparent vertical angle due to the specific side force. As this signal differs from the roll velocity of the aircraft a physiological limiting function limits the rate of change similar to the rate limiting block of the CWA. Unaffected by sum S4 the second output signal therefore is a low-pass filtered angular position due to a lateral specific force. Notwithstanding the physiological limiting, the AVF therefore realizes a set of complementary filters for the translational and the rotational output.

The red line in **Fig. 2** shows the response of the AVF to the input signal of a taxi turn on ground. Only minor differences in the filter response to the CWA can be seen in all three plots. This is not surprising because, notwithstanding the filtering method in use, the main problem of reproducing low-frequent specific forces by a

combination of translational accelerations and angular positions remains: Without any distortion of the pilot this is possible as long the translational space envelope allows a similar translational acceleration or if the rate of the specific force is low enough to rotate the cabin below the pilot's perception threshold. All other cases, like the given idealized example, cannot be done optimally in general and therefore have to be tuned individually to the costumer's needs.

#### IV. Results for the Objective Motion Cueing Test in AVES

The discussion of how motion systems are contributing both to training effectivity and quality has gained momentum during the last years. Especially the direct and incidental costs of motion systems seem to prevent small and commuter aircraft operators to take advantage of the benefits of flight simulation training. This directly leads to the question of how to evaluate the quality of motion systems objectively. The current approach defines statistically fixed limits for a frequency domain test catalogue, the Objective Motion Cueing Test (OMCT). Meanwhile, this test is implemented in relevant certification standards like the FAA AC120-40 [15]. Therefore, an investigation is interesting of how the Apparent Vertical Filter will be able to meet the OMCT requirements.

According to Ref. [16] the OMCT consists of a set of 10 tests (see **Table 1**). They shall ensure an adequate analysis to a response of a motion system during typical flight maneuvers. These ten frequency domain tests represent idealized maneuvers in longitudinal, lateral and vertical directions. As the current paper, as well as its two predecessors [13, 14], considered a set of three idealized lateral flight phases the analysis will focus on the lateral maneuvers. Therefore, the following subsections will discuss the results that are found by in the AVES motion system, a Moog 14-ton commercial-of-the-shelf pneumo-electrical driven hexapod type used in many flight training facilities. The AVF is integrated by using the Moog Software Development Environment. Having this setup implemented, the following results for the four relevant lateral OMCT tests plus two equivalent longitudinal tests are found.

The motion tuning is derived from the one used to perform experiments for new cabin layouts with artificial external view [17] where the question of acceptable time lags between motion and visual cues for flight passengers has been investigated.

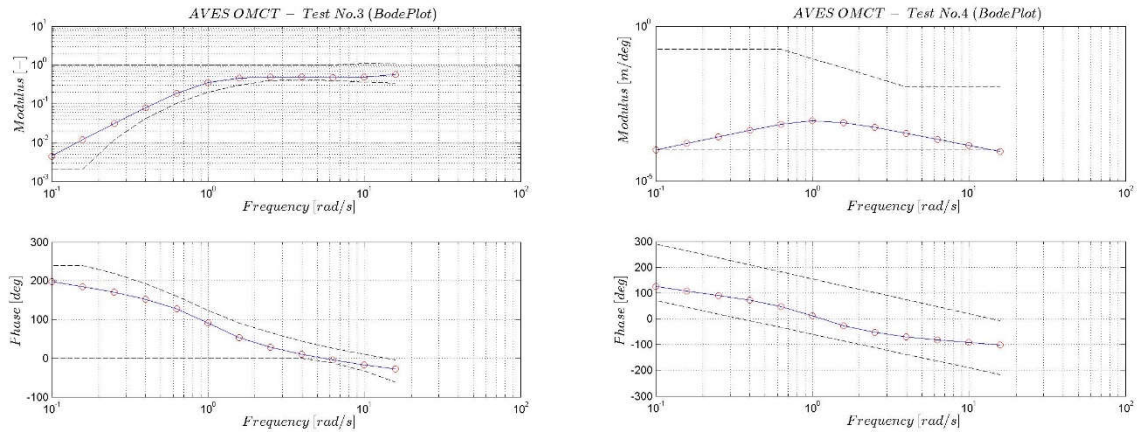
		Simulator Response Output					
		Roll	Pitch	Yaw	Surge	Sway	Heave
Aircraft Input Signal	Roll	3				4	
	Pitch		1		2		
	Yaw			5			
	Surge		7		6		
	Sway	9				8	
	Heave						10

**Table 1** The ten tests defined by OMCT and their input as well as their output signals. The tests discussed below are given in red numbers.

##### A. Test 3 and 4: Roll and Lateral Response due to a Roll Input Signal

Test 3 and Test 4 represent the reaction of the simulator due to a coordinated turn during a flight. The input signal is a pure roll-rate. The lateral specific input force remains 0. It should be noted that the vertical specific force remains 0, too. During an ideal coordinated turn, the vertical force during a flight will be increased due to the centrifugal force during the turn. But for the AVF this does not change the response due to this test and can therefore be disregarded here.

Test 3 evaluates the simulator roll response due to an aircraft roll input. As no centrifugal force can be impressed in a simulator, it is not possible to roll the simulator cabin just like an aircraft does without suffering a noticeable side force. Only for short term maneuvers the ration of the roll rate of the aircraft and the simulator can reach 1 as long as the side force which is subsequently caused can be compensated by a lateral acceleration. Of course, this compensating movement is strictly limited by the usable lateral space. For this reason, a high-pass filter needs to limit the response to low-frequent input signals. High-frequent signals on the other side will not be diminished. An overall gain of 1 results in a corresponding modulus in Fig. 5(a) for all lateral maneuver input signals.



**Fig. 5** The results of OMCT test 3 (Fig. 5a, left) and test 4 (Fig. 5b, right) applied to the AVF. The blue lines are the results of the tests while the grey lines are showing the limits defined by the OMCT according to [19].

Test 4 analyzes the lateral force in the simulator with respect to a pure roll input (Fig. 5a). The aim of the filter should be to ensure that no side force is experienced by the pilot. As a consequence, the side force shall be as low as possible. If we accept the need to limit low-frequent maneuvers as discussed above, the lateral force can be 0 in theory as long as the remaining space envelope allows a compensating lateral acceleration. As a consequence of such a compensation a lateral space is needed which means that a high-frequent roll can be represented correctly while a low-frequent aggressive turn cannot. The defined test signal of the OMCT may be seen as a result of the latter type so that the AVF shall be able to respond in a way that no side force occurs in the simulator.

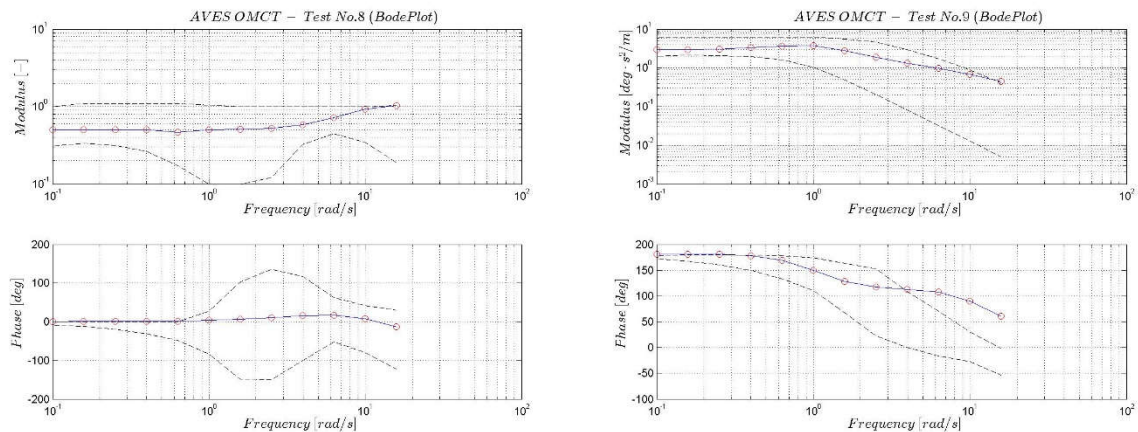
The results shown in Fig. 5(b) justify this assumption. The modulus of the side force represents less than a thousandth for almost the complete frequency range and is therefore well below the limit according to [19] which is defined to be acceptable by the test. The phase shift does remain within the acceptable area. But this result is of not much relevance due to the small order of magnitude of the resulting side force and due to the fact that the OMCT definition itself indicates that the area outside the acceptable area is named as “caution area” indicating that the reaction of the motion cannot simply be judged as a false cue.

It should be noted that due to the composition of the AVF this result can be expected for any cut-off frequency chosen by the operator of a simulator. Referring to the explanations of Ref. [14] one could see that the high-pass filter will govern both, the translational and the rotational output in the same way. This always leads to a well synchronized filter response of the two output signals. As a consequence, during a coordinated turn, the AVF is able to represent the direction of the apparent vertical correctly at any time.

### B. Test 8 and 9: Lateral and Roll Response due to a Lateral Specific Force Input

Test 8 and test 9 show the reaction of the simulator due to a pure lateral specific force without any roll input. This corresponds to a taxi turn on ground maneuver as discussed earlier in this paper. Test 8 shows the ratio of the lateral specific force observed in an aircraft with that in the simulator while test 9 shows the corresponding roll response. Again, it should be noted that the overall gain factor chosen in the two filters is 0.5 which is a common value for flight training simulators.

In general, very low-frequent and very high-frequent maneuvers can be well represented by a simulator. High-frequent maneuvers are easily done by translational accelerations. Low-frequent maneuvers can be represented by slow tilt-coordinated and therefore rotational attitudes. Because of the low rotational velocity, the rotation of the cabin will not be perceived by the pilot. Consequently, no false cue occurs. The trouble starts where the given space envelope does not allow the filter to answer with translational accelerations and a rotation needs to be executed above the cueing threshold of the pilot. In this case a painful compromise must be found even if it does not fit in with all the demands. It is possible either to rotate the cabin faster which will lead to a false rotational cue or slower which will prolong the change of the translational force while all other cues indicate that the force which is felt should be constant. Both false cues, which depend on the subjective perception of each pilot, may lead to physical uneasiness up to motion sickness. To make things worse the decision if one of the measures mentioned above is better than the other one depends very much on individual personalities and moreover on daily performance of the pilots.



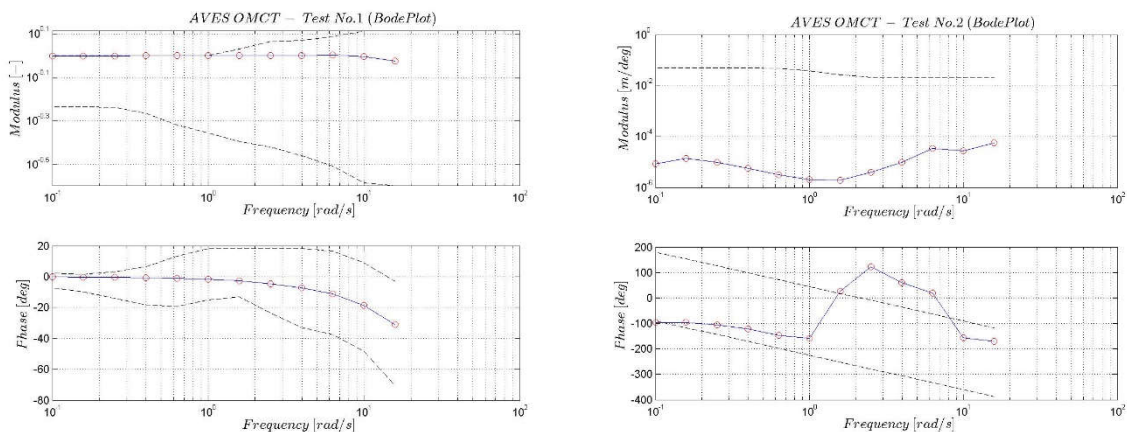
**Fig. 6** The results of OMCT test 8 (Fig. 6a, left) and test 9 (Fig. 6b, right) applied to the AVF. The blue lines are the results of the tests while the grey lines are showing the limits defined by the OMCT.

The result of test 8 (Fig. (a)) confirm the statements made above. It should be noted that ground maneuvers are not performed with the given filter setting. The reaction of the motion system is very similar to the input signal for high and low frequent signals. This leads to a gain of 1 while the phase differs from zero at the higher frequencies. For the frequencies below 10 rad/s the gain is less than 1. This is the result of the gain setting in the AVF of 0.5. This factor allows a constant gain for almost the complete frequency range. Alternatively, a higher gain may be used which will lead to drop in the gain for frequencies between 1 and 5 rad/s due to a limited angular velocity to avoid motion sickness tendencies. From the filter point of view, it is easily possible to allow higher angular velocities leading to a gain of 1 and a phase near zero even for these frequencies. Consequently, one may argue that this would be an example where the OMCT indicates a good response where there is none. But without knowing the technical constraints of the given motion system, e. g. the lateral space envelope, it is not possible to accept or reject such results just upon the basis of this Bode plot.

The result of test 9 (Fig. (b)), especially the modulus, shows that the reaction is well within the requirements according to [19]. Nevertheless, subjective feedback indicates that the roll reaction may be too aggressive for some pilots. As said above the filter setting is not used for a ground maneuver which explains why a limitation of the rotational speed to prevent motion sickness is not needed here. It is most likely that a normal pilot would perceive the wrong rotation in case of a taxi turn on ground and might complain about that.

### C. Test 1 and 2: Pitch and Surge Response due to a Pitch and a Surge Specific Force Input

Test 1 and test 2 are supposed to be longitudinal tests. A pitch input signal is accompanied by a longitudinal specific force. It can be interpreted as a maneuver that is similar to an alternating climb and descent but without a change in the vertical specific force. But due to the composition of the input signal this test allows a good conclusion of how a steady side-slip maneuver with a roll input complemented by a lateral specific force will be responded by the AVF. Test 1 shows the pitch response of the simulator which should be very close to the pitch input signal. Test 2 gives the longitudinal acceleration response to a pitch input which should be zero because the simulator only needs to rotate in the same way the aircraft does to represent the pitch cue correctly.



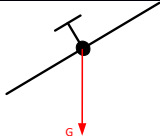
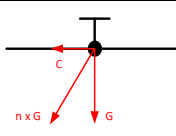
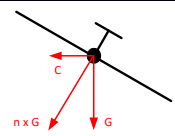
**Fig. 7** The results of OMCT test 1 (Fig. 7a, left) and test 2 (Fig. 7b, right) applied to the AVF. The blue lines are the results of the tests while the grey lines are showing the limits defined by the OMCT.

Test 1 shows a very good coincidence of input and output signals (**Fig. 7(a)**). This indicates indeed that the simulator cabin just pitches up and down the same way the aircraft does. This statement is supported by the result of test 2 (**Fig. 7(b)**), where hardly any translational acceleration response can be seen. The phase shift of test 1 is small except at higher frequencies. These phase shifts are the result of low-pass filters that are needed e. g. to protect the simulator against frequencies of more than 10Hz or to smooth aircraft model output signals. It should be noted that the phase shift could be limited by increasing the data integrity and that the core filter method itself does not contribute to this phase shift.

The graph for test 2 (**Fig. 7(b)**) shows an overall good result. The phase for the low and high frequencies is not far outside the thresholds that are defined as the area of fidelity by OMCT. Only for tests above 1 rad/s it is beyond the limits in the so-called caution area. According to the OMCT test definition such a deviation, accompanied by the low gain does not have a significant meaning.

## V. Conclusions

The representation of the aircraft maneuvers in a flight simulator can be realized by a motion system addressing the main human perception cues, the translational acceleration and the rotational velocity. Therefore, it is possible to characterize any maneuver by the occurrence of those cues. A maneuver is accompanied either by a translational acceleration resulting in a specific force, by a rotation or by both of them. For lateral maneuvers these characteristics correspond to a taxi turn on ground, a coordinated turn during a flight and a steady side-slip or lateral hover movements during a flight (see Table 2).

Maneuver	Steady Side-Slip / Hover	Taxi Turn on Ground	Coordinated Turn
Side Force	yes	yes	no
Rotation	yes	no	yes
Forces			
Apparent Vertical represented by the AVF	Same attitude as in aircraft, no filtering	Tilt-coordination similar to other filter concepts	Very good match because the roll and the compensating lateral response are controlled by the same high-pass filter
Magnitude of Force represented by the AVF	Same attitude as in aircraft, no filtering	Complementary filter for roll and lateral response Physiological limiting for roll response	
			Simulation of load factor for high-frequent input signals possible; For low-frequent maneuvers only 1g is available

**Table 2 Capability of the Apparent Vertical Filter to represent the three lateral maneuvers.**

The main idea of the Apparent Vertical Filter is to improve the pilot's perception by comparing the input signals from the aircraft model and optimizing the command of the motion system. The optimization criteria are the direction and the magnitude of the specific force and the rotation felt in the cockpit. Due to the limited space envelope of the motion system, a perfect coincidence of specific forces, especially in terms of their magnitude, is not possible in the simulator for all the maneuvers. The aim therefore is to provide at least the correct orientation of the force vector while the rotation should be represented as far as possible.

This paper presents the proof-of-concept for the AVF with respect to a taxi turn on ground maneuver. The specific force input signals are given for the defined idealized test. The response to those signals is discussed for a classic washout filter algorithm and the Apparent Vertical Filter. It could be shown that for this case the Apparent Vertical Filter does not reproduce the aircraft specific force significantly better than a classical washout filter algorithm. Summarizing the results of Ref. [13, 14] and this paper, for all three lateral maneuvers the AVF qualitatively shows the performance given in Table 2.

For longitudinal motion cues equivalent maneuvers could be defined. A steady-state side-slip or longitudinal hover has the same input signal logic as an un-accelerated climb or descent. A taxi turn on ground corresponds to a take-off acceleration or braking while a coordinated turn can be compared with a parabolic flight or a flare-out just before touchdown. A pure vertical acceleration similar to a ground bump or vertical gust and a yaw rotation complete a set of eight conceivable maneuvers in total.

Six out of those eight maneuvers are currently part of the OMCT:

- Tests 1 and 2: Un-accelerated climb/descent (longitudinal)
- Tests 3 and 4: Coordinated Turn (lateral)
- Test 5: Yaw rotation (vertical)
- Tests 6 and 7: Acceleration / braking on ground (longitudinal)
- Tests 8 and 9: Taxi turn on ground (lateral)
- Test 10: Ground bump or gust (vertical)

To show the basic response of an Apparent Vertical Filter to the OMCT six tests are of main interest: Tests 3, 4, 8 and 9 for lateral maneuvers and tests 1 and 2 for the longitudinal counterpart of a steady side-slip in flight. It could be demonstrated that the AVF is able to fulfill the requirements of these tests.

- For a coordinated turn no side force is expected as long as the lateral space envelope is able to ensure a compensating acceleration for the roll attitudes of the simulator cabin.
- For a pure lateral acceleration, the AVF will respond similarly to other filtering methods having to consider the contradictory objectives “accurate specific force” and “imperceptible rotation”.
- A steady side-slip or hover maneuver will be represented the same way like in an aircraft by the AVF because the filter does not manipulate the input signal leading to an unmodified output signal.

For the remaining tests a surprise is hardly supposed. Because tests 6 and 7 are the longitudinal equivalent of tests 8 and 9 a similar behavior can be expected. The responses to vertical maneuvers (tests 5 and 10) are more or less the same like those of other filter concepts because no tilt-coordination can be used. Therefore, a high-pass filter is the only way to limit the motion system’s response to the given space envelope like any other cueing algorithm leading to similar test results. In summary the AVF will mostly fulfill the requirements of the OMCT. Because the steady side-slip or hover maneuver will be done correctly for any filter setting, only for the two maneuvers left, the taxi turn on ground and the coordinated turn in flight, a compromise needs to be found for a given training syllabus.

## References

- [1] Link, E. A., Binghampton, NY, US Patent Specification for a “Combination Training Device for Student Aviators and Entertainment Apparatus,” Patent No. 1,825,462, filed 29. Sep. 1931
- [2] The ASME History and Heritage Committee, “The Link Flight Trainer – A Historic Mechanical Engineering Landmark,” Roberson Museum & Science Center, The Link Foundation, Binghampton, NY, 2000
- [3] Longridge, T., Ray, P., Boothe, E., Bürki-Cohen, J., “Initiative Towards More Affordable Flight Simulators for U.S. Commuter Airline Training,” Proceedings of the Royal Aeronautical Society Conference on Training – Lowering the Cost, Maintaining Fidelity, London, UK, 1996
- [4] Bürki-Cohen, J., Sparko, A. L., Jo, Y. J., Go, T. H., “Effects of Visual, Seat, and Platform Motion During Flight Simulator Air Transport Pilot Training and Evaluation,” Proceedings of the 15th International Symposium on Aviation Psychology, Dayton, OH, 2009
- [5] Advani, S. K., Hosman, R. J., “Revising Civil Simulator Standards – An Opportunity for Technological Pull,” AIAA Modelling and Simulation Technologies Conference and Exhibit, Keystone, CO, 2006
- [6] Hosman, R. J., Advani, S. K., “Are Criteria for Motion Cueing and Time Delays Possible? Part 2,” AIAA Modelling and Simulation Technologies Conference and Exhibit, Boston, MA, 2013
- [7] Hodge, S. J., Manso, S., White, M. D., “Challenges in Roll-Sway Motion Cueing Fidelity: A view from academia”, Royal Aeronautical Society Flight Simulation Group Conference, London, UK, 2015
- [8] Hodge, S. J., Perfect, P., Padfield, G. D. White, M. D., “Optimising the roll-sway motion cues available from a short stroke hexapod motion platform,” The Aeronautical Journal, Volume 119, No. 1211, 2015, pp. 23,-44
- [9] van Biervliet, F., “A Side Force to Reckon with”, CAT Magazine, Issue 5/2007; pp. 12-13
- [10] van Biervliet, F., La Hulpe, Belgium, European Patent Specification for a “Method to Control the Movements of a Flight Simulator and Flight Simulator Implementing such Method,” European Patent No. EP 1 946 193 B2, filed 12 Oct. 2006
- [11] Seehof, C., Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany, German Patent Specification for a “Verfahren und Vorrichtung zur Ansteuerung eines Simulators,” Patent No. DE 10 2015 102 459 B4, filed 03. Nov. 2016
- [12] Reid, L. D., Nahon, M. A., “Flight Simulation Motion-Base Drive Algorithms: Part I – Developing and Testing the Equations,” UTIAS Report No. 296, University of Toronto, Toronto, Canada, 1985
- [13] Seehof, C., Buch, J.-P., Raab, C., Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany, “The Force is With You – The Apparent Vertical Filter Concept,” AIAA Modelling and Simulation Technologies Conference and Exhibit, Denver, CO, 2017
- [14] Seehof, C., Fischer, M., Seefried, A., Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany, “The Apparent Vertical Filter Concept – Effects of Driving on a Slope,” Driving Simulator Conference 2017 EuropeVR, Stuttgart, Germany, 2017
- [15] Federal Aviation Administration, “Flight Simulation Training Device Qualification Standards for Extended Envelope and Adverse Weather Event Training Tasks,” Federal Register, Vol. 81, No. 61, 14 CFR Part 60, Docket No. FAA-2014-0391, Amdt. 60-4, Washington D.C., 2016
- [16] Hosman, R., Advani, S., “Design and Evaluation of the Objective Motion Cueing Test and Criterion,” The Aeronautical Journal, Vol. 120, No. 1227, pp. 873 – 891, London, UK, 2016
- [17] Stelling, D., Hermes, M., Huelmann, G., et al., “Hi-Tech Windows in the Aircraft Cabin: The Impact of Display Latencies on Passengers’ Comfort,” Building and Environment, Vol. 174., ISSN 0360-1323, 2020
- [18] European Union Aviation Safety Agency, “NPA 2020-15 – Update of the flight simulation training device requirements,” Köln, Germany, 2020
- [19] International Civil Aviation Organization, “Manual of Criteria for the Qualification of Flight Simulation Training Devices,” 3 ed., vol. I, ICAO, Montreal, Canada, 2009.