Understanding Motion Cueing: Two Sides of Newton’s Second Law

Stroosma, O.

DOI
10.2514/6.2025-0977

Publication date
2025

Document Version
Final published version

Published in
Proceedings of the AIAA SCITECH 2025 Forum

Citation (APA)
Stroosma, O. (2025). Understanding Motion Cueing: Two Sides of Newton’s Second Law. In *Proceedings of the AIAA SCITECH 2025 Forum* Article AIAA 2025-0977 https://doi.org/10.2514/6.2025-0977

AIAA SciTech Forum
6-10 January 2025, Orlando, FL
AIAA SCITECH 2025 Forum

10.2514/6.2025-0977

Understanding Motion Cueing: Two Sides of Newton's Second Law

Olaf Stroosma*
Delft University of Technology, Delft, The Netherlands

Motion cues are one of the most challenging aspects of human-in-the-loop vehicle simulators. The real vehicle cues can only be presented in a highly distorted way, so it is important to understand what these cues look like and which aspects are important for the human controlling the vehicle. This paper describes two complementary ways of assessing (translational) motion cues: accelerations plus gravity, and specific forces. These perceived cues can be constructed from different components of Newton's Second Law and are fundamentally equivalent. The paper shows how the situation heavily favors one representation or the other in understanding the motion cues to be presented. When assessing the cues in flight, the specific force formulation is superior as it leverages flight dynamics knowledge and intuition to predict and explain the form of the cues. The paper gives a number of examples to illustrate this claim, supported both by analysis and by measurements in an instrumented business jet and a motion-based flight simulator.

I. Nomenclature

a = acceleration
F = force
F_{nf} = non-field force
f_s = specific force
f_x = longitudinal specific force
g = gravitational acceleration
m = mass
α = angle of attack
θ = pitch angle

II. Introduction

High-end flight simulators usually are equipped with what are colloquially called motion systems, but are more properly referred to by EASA as "force cueing motion systems" [1]. The term motion system elicits a mental model of the goal of such systems as the replication of the motion of the aircraft, more specifically the translational and rotational accelerations. Although for rotational motions this is generally a very useful mental frame, interpreting the translational cues as "aircraft accelerations plus gravity" can lead to misinterpretations and difficulties in predicting the expected cues, which in turn might lead to incorrect design or tuning of the motion cueing algorithms driving the simulator.

In this paper the mental model of translational "motion" cues as representing the motion of the aircraft will be critically assessed. An often more useful frame will be explained, in which the linear motion cues are regarded as specific forces acting on the aircraft [2]. As this more closely matches the perceptual mechanism in the human pilot, as well as the well-understood flight dynamics of the aircraft, this model is hoped to benefit motion cueing practitioners in their understanding of the cues to be reproduced.

The paper starts by examining the vestibular perception of humans, with a focus on the linear sensors (the otoliths), in section III. Next, in section IV the problem is examined from the point of view of aircraft flight dynamics, which provides the most insight in the shape of the required cues. In section V the focus shifts to the simulator's motion cueing algorithm, and how the proposed mental model fits into a representative example algorithm. The paper ends with a conclusion in section VI.

---

[*] Senior Researcher, Faculty of Aerospace Engineer, Control & Simulation, Kluyverweg 1, Senior AIAA Member.

III. Motion Perception

Although motion through the world is most directly perceivable visually by changing positions, attitudes, and velocities, the term motion cues in the flight simulation context is usually reserved for cues that are generated by moving the simulator cabin. The resulting sensations on the human body range from tactile (pressure on the body where it touches the seat) to proprioceptive, and vestibular (the sense of balance).

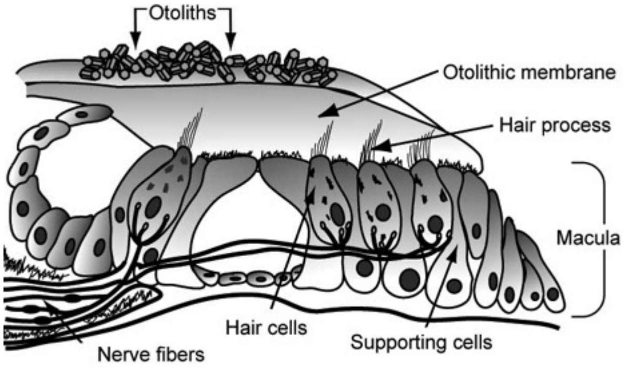


Fig. 1 Otolith organ. Source: NASA.

In the conventional explanation of translational motion perception through the vestibular system, the otoliths in the inner ear (Figure 1)are introduced as sensors for head tilt and acceleration [3]. If the body is accelerating, the calcite crystals are said to be lagging behind, deforming the gelatinous membrane they rest upon, and stimulating the hair cells protruding into the membrane. A similar situation occurs when the head is stationary and tilted with respect to gravity. The crystals are now "weighing" on the membrane and again cause it to deform.

These two descriptions are technically correct, although they seem to indicate two different mechanisms being at play. From a physical standpoint, however, it can be argued that both these situations can be described by the single mechanism of *specific forces*. Specific forces are defined as the non-field forces acting on a body, per unit mass of the body . Field forces excluded from this definition are not only gravity, but also electromagnetic forces, although those do not play a role in the current discussion. The forces acting on a body F are related to the body's acceleration a and mass m by Newton's Second Law in Equation 1.

$$F = m \cdot a \tag{1}$$

Splitting the forces into non-field (F_{nf}) and gravity forces ($m \cdot g$), dividing by the mass, and rearranging the terms gives an expression for the specific forces f_s and its relationship to acceleration and gravity in Equation 2

$$F_{nf} + m \cdot g = m \cdot a \Rightarrow f_s = \frac{F_{nf}}{m} = a - g \tag{2}$$

Equation 2 shows that the explanation of otoliths as sensors of acceleration and (the reverse of) gravity is fully equivalent to the explanation of them as specific force sensors, as long as all forces acting on the human body are taken into account, including any reaction forces. Sitting in a stationary and upright position, the upward 1g "gravity acceleration" sensation can equivalently (and arguably more accurately) be described by the upward seat reaction (specific) force.

When looking at the physics of the otoliths, the specific force explanation can be used to describe both the acceleration and tilt scenarios in a unified way. When accelerating in the horizontal plane, a corresponding force must be present, either the thrust from an aircraft engine, or tire forces in a car. This force acts on the base of the otoliths and can only be transferred to the otolith crystals by a shear force in the membrane. This shear force then causes a perceivable deformation due to the elasticity of the membrane. In the tilted head case, the external force is now a seat reaction force and the shear force works in the same manner. The force of gravity (per unit mass) works equally on both the otolith crystals and the rest of the body, and thus produces no shear force in the membrane or any neural stimulus, even though it balances the seat reaction force to prevent any acceleration. In this sense the otoliths are fundamentally incapable of detecting gravity forces. In the situations where they are conventionally said to detect gravity, they are actually sensing the reaction forces, which also directly explains the apparent change in sign between the actual gravity force and the perceived "gravity acceleration".

With the gravity force being undetectable by the vestibular system, but definitely contributing to the final kinematic acceleration, the otoliths become a highly unreliable sensor of this acceleration. The sensed specific force can differ from the acceleration motion cues by g in any direction. Without any disambiguation (visual, instrument, or other) cues, *the otoliths should not be considered as motion sensors in an aerospace context*.

Nevertheless, in many day-to-day and non-aerospace situations, the apparent dual use of the otoliths in sensing both translational accelerations and head tilt can still be useful. Tilting one's head while sitting stationary indeed produces the sensations according to this head tilt explanation. Accelerating in a horizontal plane, such as when driving a car, can also be fully explained by the acceleration explanation, without having to consider the car's tyre forces. The explanation becomes cumbersome when accelerations and gravity components both start playing a role, such as in aerospace applications. Perhaps the clearest example is the lack of vestibular cues in a constant planetary orbit. Since the simple explanation of a lack of gravity force is obviously false, an elaborate explanation of the centripetal and tangential accelerations in the spacecraft's circular or elliptical orbit and how they balance with the gravitational forces, must be constructed to explain the lack of cues. The alternative explanation explored in this paper can directly explain the vestibular cues by the lack of external aerodynamic or thrust forces. It has the added benefit of directly explaining the expected vestibular cues in cases where small aerodynamic drag or rocket thrust forces start playing a role. These can be understood to be directly perceived, without having to reconstruct the spacecraft's acceleration and orientation with respect to the gravity vector. To further explore this concept, the next section will apply the force-centric explanation to situations in the earth's atmosphere that are more relevant in the flight simulation context.

IV. Flight Dynamics

The forces acting on an aircraft's center of gravity can be roughly divided into aerodynamic, propulsion, and ground reaction forces along the three body axes of the vehicle. The aerodynamic forces are governed by the airflow around the wings, fuselage and appendages, and commonly represented as non-dimensional coefficients multiplied by the dynamic pressure ($\frac{1}{2}\rho V^2$). The coefficients in turn are mostly determined by the angles of attack and sideslip [4, p. 21]. For a fixed-wing aircraft the propulsion forces from the engines are determined by the throttle settings by the pilots or the auto-throttle. Finally, the ground reaction forces are transmitted to the vehicle through the tires and landing gear.

The specific forces perceived by the pilot are slightly different from those at the aircraft's center of gravity. Due to the distance from the pilot station to the center of gravity, rotations of the aircraft will cause additional translational cues in the flight deck, namely the centripetal and Euler accelerations. Depending on the size of the aircraft, these cues could be very noticeable, e.g., the lateral (sway) cues when aggressively yawing the aircraft in a decrab maneuver [5]. Although these cues could be considered as (specific) forces acting on the pilot's seat and body, they would take the form of structural forces to maintain the integrity of the aircraft as a rigid body, and are thus not easy to interpret. These additions to the center of gravity cues are most easily interpreted as additional accelerations due to rotational rates and accelerations, and the distances between center of gravity and pilot. Due to their transient nature and consequent lack of influence on the long-term pilot perception, these kinematic cues will not be discussed further in this paper.

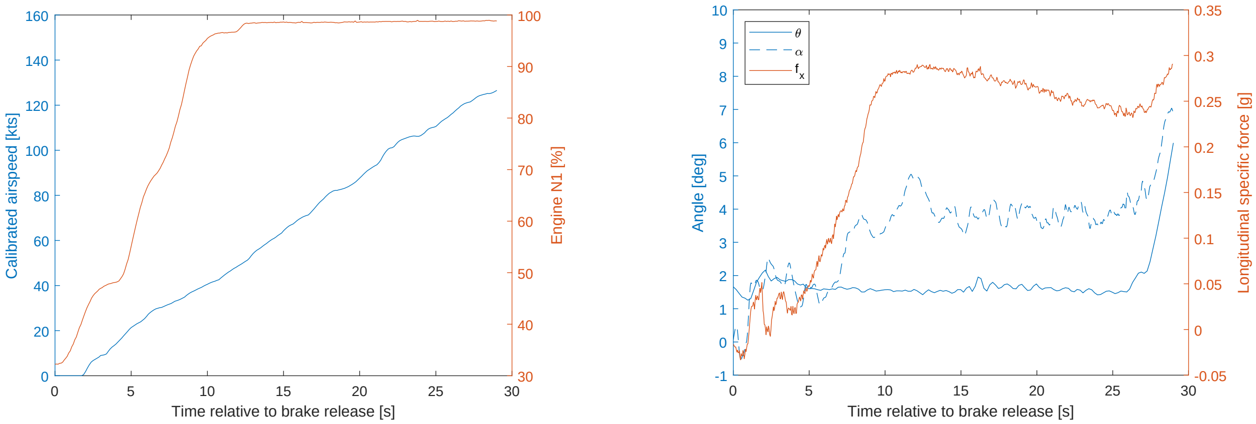
Instead, this section will examine how the forces on the *center of gravity* relate to the perceived motion cues in a number of maneuvers in order to demonstrate the power of the specific force explanation.

For some maneuvers flight test data is included from an instrumented Cessna Citation II aircraft [6]. The longitudinal motion cue is the low-pass filtered output from a dedicated Inertial Measurement Unit (IMU). This signal was confirmed to match the output of both of the aircraft's regular Attitude and Heading Reference System (AHRS) units.

A. Take-off

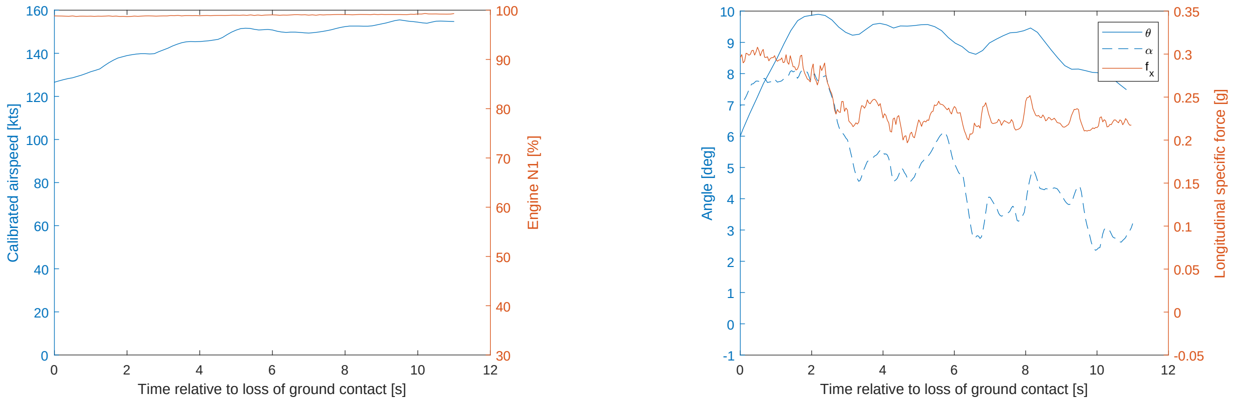
In some situations not all the forces can be easily determined, but the resulting accelerations and aircraft attitude are quite clear. In those cases the conventional translational motion cue description of kinematic and "gravitational" acceleration is the most useful. A clear example is the takeoff roll and initial rotation (Figure 2). During this phase the aircraft accelerates horizontally, which will be felt directly as a longitudinal motion cue. Vertically the aerodynamic lift and vertical gear forces vary continuously, but since the aircraft does not climb, it is clear that there is no vertical acceleration and only the 1-g gravitational "acceleration" is felt. Although the momentary kinematic acceleration is difficult to extract from the current flight test data, the average acceleration over the 13 seconds at takeoff thrust before the start of rotation (t=13 to 26 seconds in Figure 2) equals approximately 0.25 g, which corresponds to the measured longitudinal specific force in Figure 2b.

When the aircraft starts to rotate, the forces at play become even more difficult to intuitively assess, especially the ground reaction forces. Conversely the (still horizontal) kinematic acceleration of the aircraft and the gravity component



(a) Velocity and engine **(b) Angles and specific force**

Fig. 2 Takeoff acceleration and initial rotation - flight data



(a) Velocity and engine **(b) Angles and specific force**

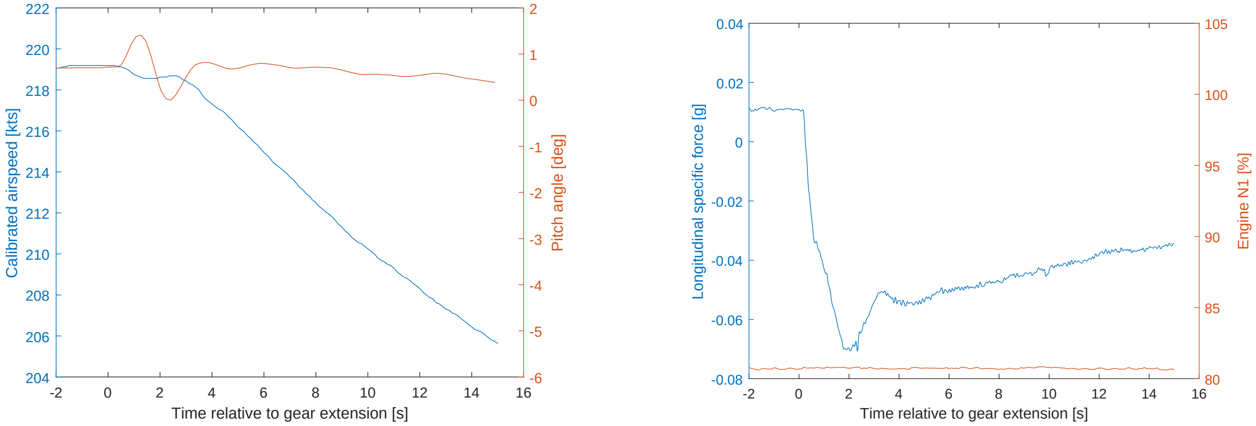
Fig. 3 Takeoff rotation and climb out - flight data

due to the aircraft's pitch angle are more easily understood. As long as the wheels are in contact with the ground, the longitudinal motion cue shows similar behavior as the aircraft pitch angle (last three seconds in Figure 2b). Although the pitch change of 4 degrees contributes a specific force change of 0.07 g, the aircraft's velocity increase also flattens out in this phase, resulting in a net increase of 0.05 g in specific force.

The behavior changes as soon as the aircraft leaves the ground and the ground reaction forces no longer play a role (Figure 3, which starts as the radio altitude becomes non-zero). Now only the aerodynamic and propulsion forces (assumed constant in this discussion) determine the motion cues. As the longitudinal aerodynamic force coefficients are largely determined by the angle of attack, the surge force coefficient no longer tracks the aircraft pitch angle, but the angle of attack, *irrespective of the aircraft's attitude*. This is most clearly visible in the first 4 seconds of Figure 3b, where the angle of attack and longitudinal specific force flatten out while the pitch angle continues to rise. In general, the specific force in a shallow accelerating climb flown with the same angle of attack as a steep constant-speed climb will yield the same aerodynamic coefficients and thereby only differs through the changing dynamic pressure with airspeed. There is no need to consider the aircraft's attitude, or the acceleration that results from the combination of aerodynamic, propulsion, and gravity forces, as the angle of attack and dynamic pressure are enough to get a complete picture.

B. Turns

When making a turn, the (lateral) motion cue expressed as acceleration and gravitational component becomes even more unwieldy, especially in the cases of climbing or descending turns. The aircraft's bank angle interacts with the lift force and aircraft weight to generate a centrifugal acceleration. Any lack of coordination will only add to the



(a) Velocity and pitch angle

(b) Specific force and engine

Fig. 4 Gear extension - deceleration with constant attitude - flight data

complexity. Considering the other side of Newton's Second Law now becomes much more useful. With the lateral (sway) motion cues being dominated by the aerodynamic forces, which in turn are determined by the sideslip angle in fixed-wing aircraft [*], that angle becomes the central driver of understanding the expected motion cues. Coordinated or uncoordinated, level, climbing, or descending, all turns will have their lateral motion cues determined by the sideslip angle, irrespective of the angle of bank. The aircraft's sideslip indicator, which works by measuring the sideways specific force, is directly displaying the sway motion cue the pilot feels in the aircraft.

C. Gear extension

To further illustrate the limitations of thinking of motion cues as accelerations, consider a maneuver where an aircraft in level flight lowers the landing gear. The resulting increase in drag will be felt as a longitudinal (specific) force, and might result in a decrease of airspeed, depending on the pilot's control actions. Consider these three different scenarios:

1) The pilot keeps the aircraft level, and lets the additional drag slow the aircraft down (Figure 4)
2) The pilot drops the nose in such a way that the airspeed does not change (Figure 5)
3) The pilot keeps the aircraft level and simultaneously increases the engine throttle to prevent a deceleration (Figure 6)

In the first scenario the aircraft is decelerating with a constant attitude (Figure 4a), and the conventional motion cue explanation as deceleration works well to explain the behavior. Figure 4b shows a rapid increase in negative specific force (and deceleration), which diminishes as the velocity and dynamic pressure reduce.

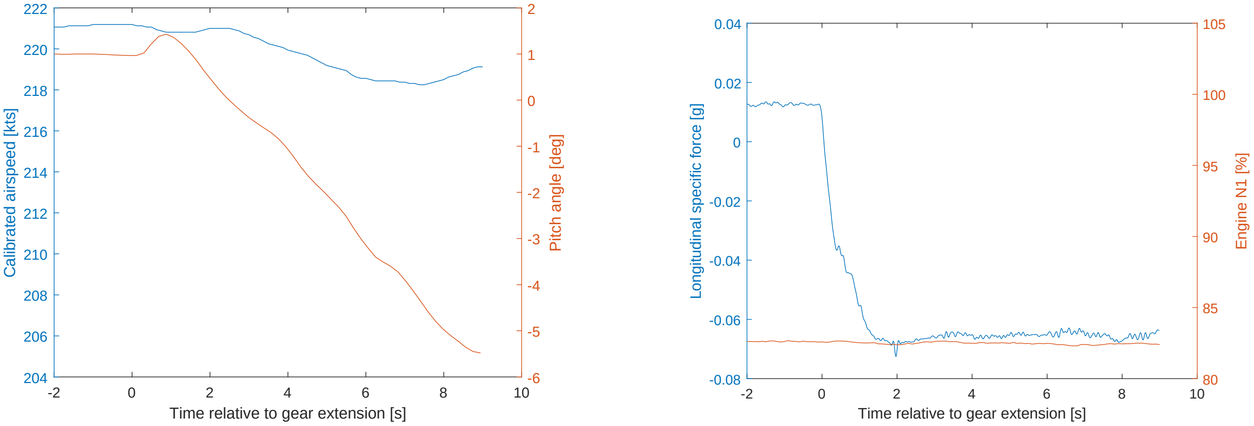
Thinking of the cue as deceleration becomes problematic in the second scenario, where the airspeed is held constant as much as possible by lowering the nose (Figure 5a). Perhaps unexpectedly, the specific force response is very similar to the first scenario, except the missing reduction due to decreasing dynamic pressure (Figure 5b). Of course the full conventional explanation also includes the gravity component, but in this case one must already start reasoning about the relative contributions of the additional drag and the gravity component to the deceleration profile. In the specific force explanation nothing fundamentally changes in the expected response, as the non-gravitational forces do not change initially.

Finally, the third maneuver also does not exhibit any deceleration (Figure 6a), but since it achieves this through perceived (engine) forces, the response differs markedly from the first two scenarios (Figure 6b).

To summarize, the primary effect of this maneuver is the added drag force, and the longitudinal motion cues are predominantly determined by this drag force alone. Only as a secondary effect is the reduced dynamic pressure from a decrease in airspeed influencing the response, as can be seen in the second half of the specific force graphs in Figures 4b and 5b. This is true for any maneuver that doesn't modify the force balance: level-flight deceleration, nose-down constant speed, or even an increased nose-up deceleration will all have the same primary surge specific force response.

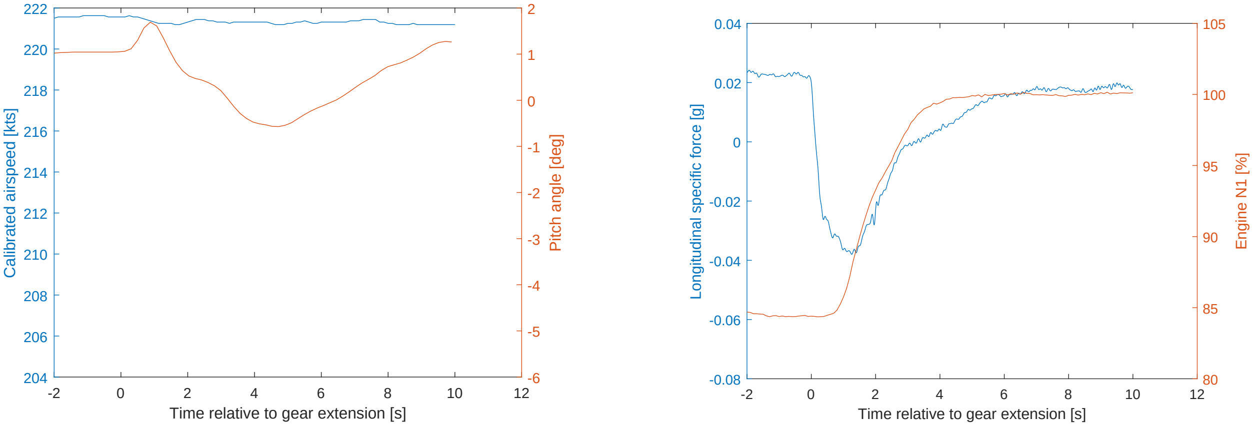
---

[*] in helicopters the tail rotor also adds a considerable amount of side force



(a) Velocity and pitch angle **(b) Specific force and engine**

Fig. 5 Gear extension - descend without deceleration - flight data



(a) Velocity and pitch angle **(b) Specific force and engine**

Fig. 6 Gear extension - engine throttle up without deceleration - flight data

D. Go-around

Another critical maneuver where pitch motions, accelerations, and thrust changes play a role, is the go-around. In this maneuver, the pilot aborts the landing and climbs out to a safe altitude. A number of events happen in relatively quick succession: the engines are spooled up to a relatively high thrust setting, the nose is brought up to arrest the sink rate and initiate a climb, the aircraft accelerates, the landing gear is brought up, and the flaps are retracted successively. Some, but not all, of these events impact the perceived longitudinal specific force. Most importantly, the increased thrust gives rise to a forward specific force. The retractions of landing gear and flaps reduce the drag and thereby also increase the forward specific force. Crucially the pitch up attitude and the acceleration do not directly impact the longitudinal specific force. Only as a secondary effect on the dynamic pressure does the acceleration play a role. Any discussions about the go-around maneuver that rely on the pitch attitude and aircraft acceleration can quickly lead to confusion and misunderstandings. In the absence of configuration or thrust changes, the longitudinal motion cue will remain constant, irrespective of aircraft pitch or acceleration.

The go-around maneuver is an important maneuver to train for pilots, as it requires the critical piloting skill of achieving the correct pitch angle after selecting TO/GA thrust [7]. The perceptual challenge in the absence strong visual cues is that the pitch attitude is not directly perceivable with the otoliths but only as an integral of the vestibular system's pitch rate sensors. Interpreting the surge specific force as a pitch attitude can lead to incorrect estimates of pitch angle and incorrect pilot responses. This illusion is commonly known as the somatogravic illusion [8, p. 251].

The idea of motion cues as acceleration cues can lead to incorrect expectations about the expected perception, and possibly erroneous tuning of motion systems. An example of this confusion is this quote from McGrath et al.[9] describing the go-around maneuver.

> Speed is slow, power is rapidly applied, and the aircraft then accelerates rapidly. In the absence of helpful visual cues, this generates a strong 'tilt back' sensation that pilots interpret (incorrectly) as the aircraft may actually be in a level attitude or even a descent. This is the somatogravic illusion. Pilots may then push forward on the control column to control this (imaginary) climb, thinking they are lowering the aircraft nose back to level flight, when in actual fact they are lowering the nose into a dive. As the aircraft nose lowers, the aircraft continues to accelerate, *generating additional pitch up sensations* [emphasis added], causing pilots to lower the nose even further [9].

Although the pilot's nose-down reaction after the somatogravic illusion does indeed cause the aircraft to accelerate, this will not be reflected in the longitudinal specific force cues. If anything, further acceleration would increase the dynamic pressure and drag force, and actually reduce the forward specific force, assuming the thrust force remains constant. Flap or gear retraction on the other hand would reduce the drag and deepen the illusion, but this important issue was not included in this particular discussion. Even when this effect is included, it is sometimes erroneously related to the resulting increase in airspeed instead of a decrease in drag [8, p. 254].

Note that even with the "acceleration and gravity" explanation, the correct expected cues could be determined by noting that the additional acceleration caused by the nose down attitude is perfectly matched by an opposite "gravity" component due to this nose down attitude. The fact that this component is often forgotten highlights one of the pitfalls of the "acceleration and gravity" explanation.

V. Motion Cueing

In the simulator, the motion system has the purpose of providing specific force (and rotational) cues to the pilot, while keeping the cabin inside the limited motion space. Motion cueing algorithms translate the signals from the aircraft model to setpoints for the actuators to provide the required cues. These setpoints are usually in the form of position, velocity, and acceleration, and not in terms of force, making the "acceleration and gravity" model the easiest to understand the simulator response.

A widely used algorithm to transform aircraft cues to simulator motion setpoints is the Classical Washout Algorithm (CWA) [10][11], as summarized in Figure 7. The translational (specific force) cues follow two paths: a high-frequency part that generates simulator accelerations, and a low-frequency part in the lateral and longitudinal channels, to generate simulator tilt and use gravity for sustained cues (tilt coordination). The use of gravity by tilt coordination fits nicely in the "acceleration and gravity" model, but could also be understood in the specific force model. In that mental model, the motion system's actuators are aligned with gravity to be able to exert specific forces on the cabin without causing unwanted accelerations and the associated displacements. The actuators' forces are neatly compensated by gravity to avoid these accelerations. Although equally correct, this explanation cannot leverage any intuitive insight into the forces exerted on the simulator cabin, and thus seems less useful in understanding and explaining the mechanisms at play in the simulator.

In addition to the low-pass and high-pass translational channels, the rotational channel high-pass filters the rotational

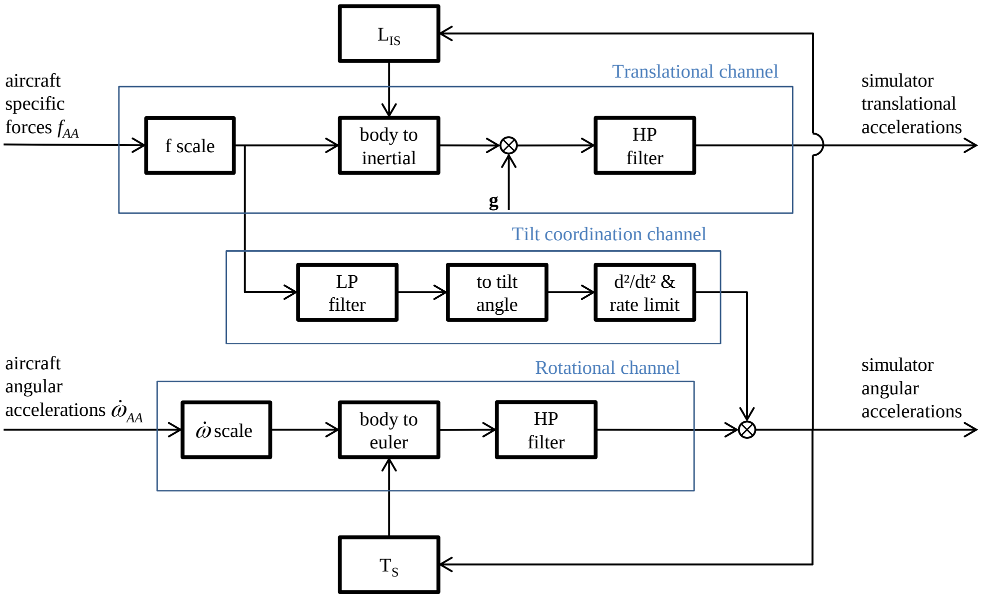


Fig. 7 Classical Washout Algorithm [11]

cues. Its output is usually added to the tilt coordination commands, causing an interaction between translational and rotational cues that is not present in the actual aircraft.

The following sections will examine how the motion cues from section IV are represented by the motion cueing algorithm. Special attention is given to the translation from specific forces in the aircraft model to acceleration and attitude of the simulator's motion base.

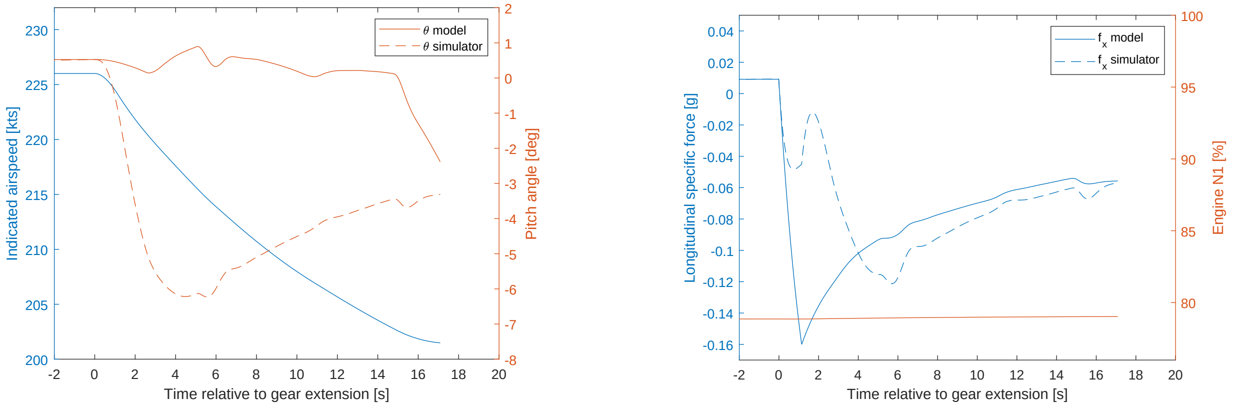
A. Take-off

At the start of the take-off roll the pilot sets the engines to take-off power and releases the brakes. The sudden excess in longitudinal specific force from the engines will pass through the high-pass translational filter and result in forward acceleration of the simulator. Due to the high order (usually second or third) of the high-pass filter, the longitudinal position will be washed out and the simulator will return to its neutral position. The long-term longitudinal specific force will be picked up by the low-pass tilt coordination, resulting in a slow nose-up rotation of the simulator. The gravity component (or alternatively the motion actuator force counteracting the gravity force along the longitudinal axis) will now provide a sustained surge cue to the pilot.

Depending on the aggressiveness of the take-off rotation and the break frequency of the pitch high-pass filter, the simulator will then replicate (part of) the pitch rotation and possibly wash it out again. This simulator pitch rotation will be combined with the low-pass tilt to replicate the changing cues during rotation. As discussed in section IV.A, the "acceleration and gravity" model can be useful to predict the cues as long as the wheels are in contact with the ground. Assuming the acceleration remains constant, the gravity component would lead to a nose-up tilt that matches the (scaled) aircraft pitch during that phase. As soon as the landing gear loses ground contact and the specific forces are determined by aerodynamic and propulsion forces, the aircraft's pitch angle loses significance and is replaced by the angle of attack. From that point on, the longitudinal specific force, and thereby the simulator tilt, will track the low-frequency changes in aircraft angle of attack. Due to the simultaneous simulator pitch from the high-pass pitch channel, it will now become more difficult to precisely predict the simulator's pitch movement based on the aircraft's response. During gentle maneuvering, where any pitch motions are heavily attenuated in the high-pass pitch channel, the simulator pitch will be determined by the aerodynamic and engine specific forces, and not aircraft attitude.

B. Turns

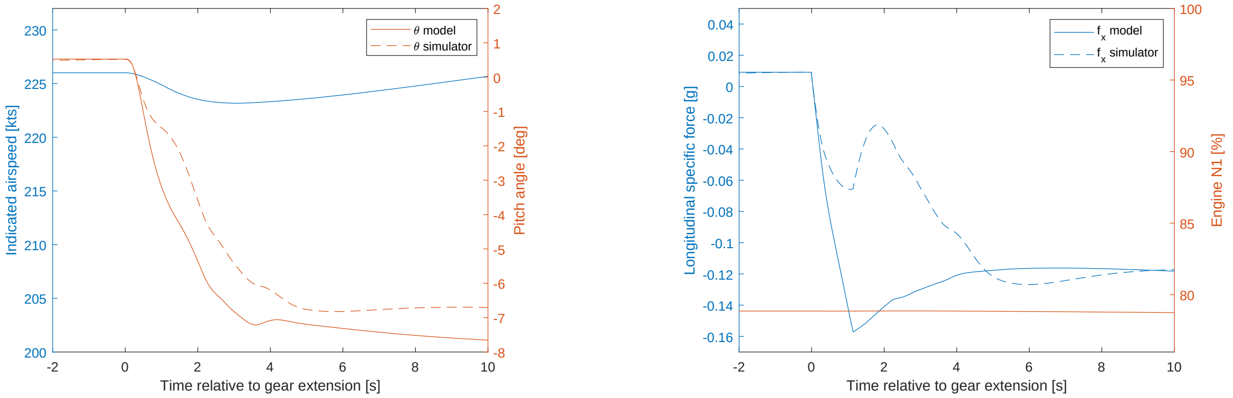
Also in the lateral case, the simulator's attitude is determined by two separate components: the high-pass filtered roll, and the lateral specific force. In aggressive maneuvers, the rotational channel will pass on the roll acceleration to



(a) Velocity and pitch angle

(b) Specific force and engine

Fig. 8 Gear extension - deceleration with constant attitude - simulator data



(a) Velocity and pitch angle

(b) Specific force and engine

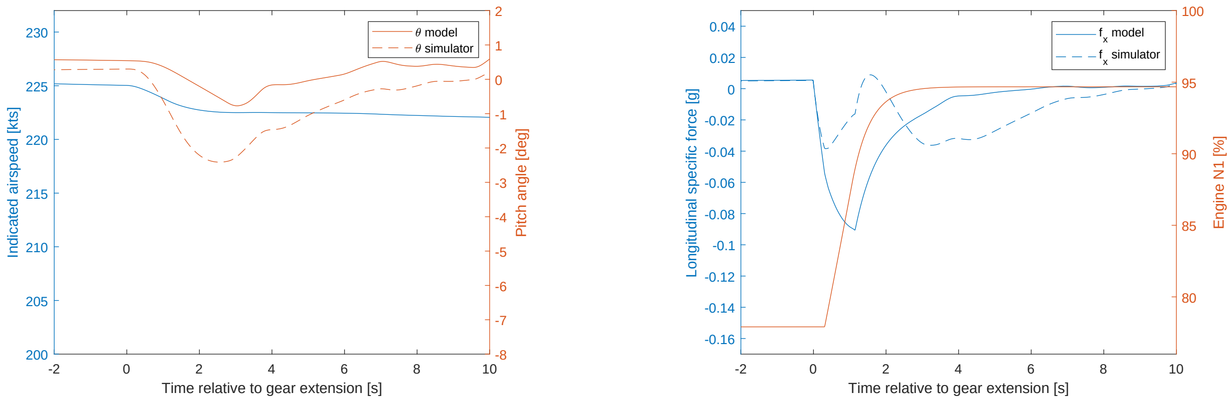
Fig. 9 Gear extension - descend without deceleration - simulator data

the simulator and wash the roll angle out to return to a neutral pose. The long term roll angle will be determined by the aircraft's sway specific force, which usually comes from sideslip (and tail rotor side force in helicopters). Especially in turns, maintaining zero sideslip is an important piloting skill, so the associated side force cue should be properly replicated in the simulator. A properly executed turn will consist of an initial simulator roll that is quickly washed out, followed by a level simulator attitude during the turn. Any lack of coordination will then be cued by tilting the simulator, allowing the pilot to compensate. There is no need to consider aircraft centripetal accelerations or attitude to predict simulator attitude, as the sideslip is the dominant factor.

C. Gear extension

The gear extension scenarios from section IV.C were replicated in the SIMONA Research Simulator [12], using a model similar to the aircraft used for the data in section IV. One of the main differences is a larger drag due extending the landing gear, as evidenced by a larger specific force response. Additionally, the motion filter was tuned to more easily show the underlying mechanism. The surge gain was set to unity and the tilt coordination break frequency was lowered to separate its effect more clearly from the high-pass surge onset and washout cues.

The first two scenarios from section IV.C that generate largely the same surge specific forces will also generate a very similar simulator response (Figure 8b and 9b). The high-frequency drag increase will lead to an aft simulator acceleration that is quickly washed out in the first two seconds and followed up by a nose-down simulator tilt to match the drag force. As the aircraft decelerates in the first scenario, the drag and thereby the perceived longitudinal specific force reduces as the dynamic pressure drops (Figure 8b).



(a) Velocity and pitch angle **(b) Specific force and engine**

Fig. 10 Gear extension - engine throttle up without deceleration - simulator data

In the scenario where the pilot pitches down to prevent aircraft acceleration, the simulator's pitch angle will again be determined by two components: the transient high-frequency pitch signal, and the low-frequency surge tilt. In this case the simulator pitch angle closely resembles the aircraft's model pitch (Figure 9a). In both cases a non-accelerating body is tilted with respect to gravity, making the acceleration and gravity model useful again to explain the cues. The power of the specific force explanation lies in the fact that it can be used in both these scenarios and everything in between. It explains how the simulator's long-term attitude can be fully understood by considering the drag forces, without having to balance aircraft acceleration and attitude changes.

As expected, the scenario where deceleration is prevented by throttling up the engines shows a long-term specific force response close to zero (Figure 10b). The simulator employs tilt coordination to match this cue.

D. Go-around

As selection of the correct pitch angle for the go-around is an important aspect of this maneuver, the (perceivable) pitch acceleration and velocity cues in the simulator should match the aircraft as much as possible to allow the pilot to employ their regular control strategy. However, the simulator pitch angle is also used to replicate the surge specific force cues in the aircraft, which have been shown in section IV.D to depend only on thrust and drag forces and not on aircraft pitch. This conflict between coupled cues such as pitch and surge is exemplary of the challenges in motion cueing. Balancing the high-frequency pitch motions through the rotational channel, and the low-frequency surge cues through the tilt coordination channel requires careful tuning of the parameters (e.g., break frequencies) in the algorithm.

As discussed in section IV.D, the go-around maneuver is prone to vestibular effects such as the somatogravic illusion. In the simulator, the tilt coordination mechanism actually causes this illusion to become a reality instead of an illusion. The sustained longitudinal specific force in the simulator is in fact directly correlated with a nose-up attitude, contrary to the situation in the aircraft, where the same cue is independent of the aircraft's attitude. By adjusting the tilt coordination parameters, the simulator rotational cues are kept to a level that is not perceived by the pilot's vestibular system, restoring the illusionary effect.

E. Motion cueing conclusion

As this section demonstrates, it is in the motion cueing algorithm that the two explanations are connected. While the input to the algorithm is shown to be most easily understood as the flight dynamics forces, the output takes the form of accelerations and gravity tilting. Since Newton's Second Law links the two, none of them are inherently more correct. Nevertheless, one or the other lends itself better to intuitive reasoning and engineering judgments, depending on the situation.

VI. Conclusion

Two equally valid characterizations of translational motion cues have been presented: the often-used "acceleration and gravity" and the specific force explanation. They form the two sides of Newton's Second Law. The analysis and examples from flight dynamics have shown how the specific force explanation provides the most insight and is the most robust against misinterpretation when considering the aircraft's motion cues, i.e. the input of the simulator's motion cueing algorithm. On the other hand, the acceleration explanation aligns best with the way the motion base itself is controlled with the output of the motion cueing algorithm.

The specific force formulation should be used when developing new or adapting existing motion cueing algorithms in order to understand how these algorithms will be excited. Also when assessing motion cues in a simulator, evaluation pilots should be aware of the cues they should expect to perceive in the real aircraft, such as a nose-high attitude not always correlating with a forward specific force.

Neither of the representations directly relate the translational "motion" cues to the kinematic motion of the aircraft. The unperceived role of the gravity force in the resulting acceleration will make "motion" cues highly unreliable as motion sensors in an aerospace setting. In that sense these translational "motion" cues do not actually cue aircraft motion. Additional visual cues to disambiguate the vehicle's attitude and thereby the direction of gravity will always be necessary to properly assess the magnitude and direction of the aircraft's acceleration.

Acknowledgments

The author thanks the members of TU Delft's Aerospace Human-Machine Systems cluster for the invaluable discussions that form the basis for this paper, and the research pilots of the PH-LAB laboratory aircraft for performing the in-flight measurements.

References

[1] *Certification Specifications for Aeroplane Flight Simulation Training Devices*, CS-FSTD(A) Revision 2, European Aviation Safety Agency, 2018. URL `https://www.easa.europa.eu/en/document-library/certification-specifications/cs-fstda-issue-2`.

[2] "Dynamic Characteristics of Flight Simulator Motion Systems," Tech. Rep. AGARD AR-144, North Atlantic Treaty Organization, 1979.

[3] Boff, K. R., Kaufman, L., and Thomas, J. P., *Handbook of perception and human performance*, Vol. 1, Wiley New York, 1986.

[4] Nelson, R. C., et al., *Flight stability and automatic control*, 2nd ed., WCB/McGraw Hill New York, 1998.

[5] Beukers, J., Stroosma, O., Pool, D., Mulder, M., and Van Paassen, M., "Investigation into pilot perception and control during Decrab maneuvers in simulated flight," *Journal of guidance, control, and dynamics*, Vol. 33, No. 4, 2010, pp. 1048–1063. https://doi.org/10.2514/1.47774.

[6] in't Veld, A. C., and Karwal, A. K., "Upgrading a multi-mission research aircraft," *Air Transport and Operations*, 2012, pp. 400–405. https://doi.org/10.3233/978-1-61499-119-9-400.

[7] *Airplane Flying Handbook*, FAA-H-8083-3C, U.S. Department of Transportation, 2021. URL https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/airplane_handbook.

[8] Previc, F. H., and Ercoline, W. R., *Spatial disorientation in aviation*, Vol. 203, AIAA, 2004. https://doi.org/10.2514/4.866708.

[9] McGrath, B., Lawson, B., Newman, M., and Rupert, A. H., "An algorithm to improve ground-based spatial disorientation training," *AIAA Modeling and Simulation Technologies Conference*, 2015. https://doi.org/10.2514/6.2015-0656.

[10] Reid, L. D., and Nahon, M. A., "Flight simulation motion-base drive algorithms: part 1. developing and testing the equations," Tech. Rep. 296, University of Toronto, 1985.

[11] Stroosma, O., van Paassen, M., Mulder, M., Hosman, R. J., and Advani, S. K., "Applying the objective motion cueing test to a classical washout algorithm," *AIAA Modeling and Simulation Technologies (MST) Conference*, 2013. https://doi.org/10.2514/6.2013-4834.

[12] Stroosma, O., Van Paassen, M. M., and Mulder, M., "Using the SIMONA Research Simulator for Human-machine Interaction Research," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, 2003, pp. 1–8. https://doi.org/10.2514/6.2003-5525.