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Just Feeling the Force: Just Noticeable Difference for Asymmetric Vibrations

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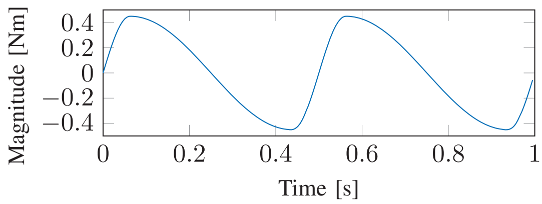
***Abstract*—Previous research showed that haptic feedback, in the form of asymmetric vibrations, can be used to provide directional cues to the operator in a laboratory setting. Nevertheless, it is unclear how these vibrations should be designed for pilots controlling their aircraft using a side-stick.This paper aims to determine the magnitude and shape for which vibrations can still be perceived as directional cues, for one fixed frequency based on literature. The threshold magnitude of two forcing function shapes (triangular and sawtooth) was determined for both pulling and pushing cues in a just-noticeable-difference experiment. Participants were asked to report the direction at varying input magnitudes while exerting different offset force levels on the stick at different positions. Results confirmed all hypotheses: they indicated a lower perception threshold for the asymmetric sawtooth shaped vibration compared to a triangular shaped; higher offset force decreased the threshold in the opposite direction; and stick position had no effect on the obtained thresholds. Based on the experiment we advise to use sawtooth vibrations with an amplitude higher than 0.094 Nm.**

I. Introduction

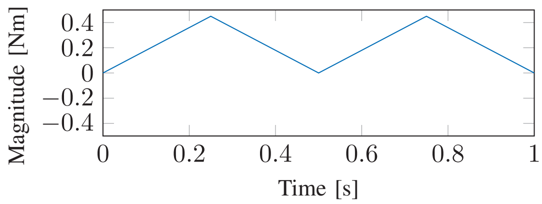
Human-machine interface environments, such as the cockpit of an aircraft, provide an abundance of visual and auditory information. Haptic feedback, i.e., force feedback through the control device, presents a different and direct way of communicating with the operator, but is still little used. Within haptics, support ranges from simple 'attention'-demanding cues to haptic shared control, mixing automation and human input. [1] The latter involves an automated system actively moving the control device, which could be unwanted when operating a vehicle near its limits. Vibrations, on the other hand, provide a cue to the operator *without* imposing a control input which makes them useful for accurate control.

Literature on vibrations shows two similar and parallel lines of research. In the first line, operators are only perceiving the signal and not actively controlling. Tappeiner et al., for example, investigated an asymmetric vibrations applied to an operator holding a magnetic flotor. [2] The vibration was asymmetric *in time*: the 'rise time' differs from the 'fall time', see Fig. 1(a). Their analysis showed that such a system can indeed be used to provide directional cues, yet requires more research when the operator is actively using the control device.

An example of the second line, where operators are perceiving and also actively controlling, is a haptic lane departure system when driving a car. Navarro et al. used pulse inputs when a lane departure was imminent and showed that participants were more inclined to follow these commands as they act as a 'motor priming' element. [4] Huang et al. investigated three variations: the forcing function shape (square, triangular pulses), amplitude (large/small) and frequency (20/10/3 Hz). The analysis of lane departures showed that a signal with small amplitude, a square shape and mid-frequency was the best compromise for practical applications. [3] These two examples show the use of vibrations which are asymmetric *in amplitude*: the upper and lower parts of the oscillation are not equal as shown on Fig. 1(b). Note that next to these two groups of vibrations, asymmetric-in-amplitude and -in-time, multiple other vibrations exist, yet this paper limits to these two.



(a) Asymmetric-in-*time* and symmetric-in-*amplitude* vibration [2]



(b) Symmetric-in-*time* and asymmetric-in-*amplitude* vibration [3]

Fig. 1. Asymmetric vibrations studied in this work

Although the last two examples show that providing a directional force cue to an actively-controlling operator is feasible, the operator could experience the *asymmetric* amplitude as a *symmetric* vibration with a shift in mean force, loosing the directional information. Hence both the asymmetric-in-time and asymmetric-in-amplitude vibrations required more investigation to transfer them to a real-life application.

The work presented in this paper is part of a project which applies haptic cues for increasing pilot awareness when controlling aircraft close to the flight envelope limits. [5], [6] First evaluations of our haptic flight envelope protection system indicate that pilots preferred rather simple cues which indicate that the aircraft is close to the flight envelope limits through a discrete 'tick on the stick'. Ideally, such a 'tick on the stick' would not interfere with pilot control actions

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(as he or she may be operating close to the flight envelope boundaries), so its magnitude should be small. But not too small, because then pilots may not perceive it at all. One of the downsides of the vibrations we used was that these did not provide advice about which direction to steer, which is valuable information when operating an aircraft near its limits.

When a pilot is flying, the side-stick can be at different positions where the vibrations might have a different effect due to the grip of the side-stick or other bio-mechanical effects. Additionally, the side-stick in consideration has a centering stiffness, which requires a force at a certain deflection. This offset force might influence the effect of the vibrations following Weber's law: higher offset forces lower the perceivability. [7]

As we want to investigate the use of vibrations on a typical side-stick manipulator to transmit both a triggering and directional cue, the goal of this research is to find the asymmetric vibration shape, its advised magnitude, and whether it depends on the side-stick position or force exerted on the side-stick. Therefore, we will determine the minimum amplitude which two shapes of asymmetric vibrations require such that pilots are able to distinguish a direction while actively exerting a force on the control device: the Just Noticeable Difference (JND) for an asymmetric vibration.

Section II explains the forcing functions design rationale. Section III describes how to obtain the JNDs in asymmetric vibrations. Results are shown in Section IV and discussed in Section V. The paper ends with conclusions in Section VI.

II. Design of Asymmetric Vibrations

All forcing functions used in this paper are intended to indicate a *direction*, which requires an *asymmetry*. This asymmetry can be either in time or in amplitude. An asymmetry in time shows itself as the difference in rise and fall time as can be seen on Fig. 1(a). It results in a side-stick which is accelerating more in one direction. Asymmetry in amplitude is a difference in the magnitude to one side as shown on Fig. 1(b). Using such a function makes the side-stick move mostly to one side.

Aside from the forcing function, pilot actions need to be considered too. The closest control task found in literature is a lane keeping task for which the use of asymmetric-in-amplitude forcing functions was considered. [3], [4] Literature shows that asymmetric-in-time forcing functions can be of interest, therefore a combination of asymmetry in time *and* in amplitude is used in this research.

Before the actual forcing functions can be discussed, one more component needs to be addressed, the link between the forcing function and the pilot: the side-stick dynamics. Whereas some literature might not fully specify the dynamics involved, initial implementations of forcing functions found that the side-stick dynamics can have a large impact on the perceivable forces and available functions.

A. Side-stick dynamics

Stick dynamics are governed by a simple mass-spring damper system, representing a side-stick used in the cockpit of commercial aircraft (with inertia, $m_{ss} = 0.2\text{kgm}^2$, spring stiffness, $k_{ss} = 35.68\text{Nm/ rad}$, damping $b_{ss} = 0.4\text{Nm/ rads}$). Limb dynamics are modelled by a spring-mass-damper system, representing the inertia of the lumped neuro-muscular system and the damping/spring dynamics of the skin combined with limbs (with inertia, $m_l = 0.07\text{kgm}^2$, spring stiffness, $k_l = 400\text{Nm/ rad}$, and damping $b_l = 12\text{Nm/ rads}$). [8] These are combined in a lumped system as shown in Fig. 2.

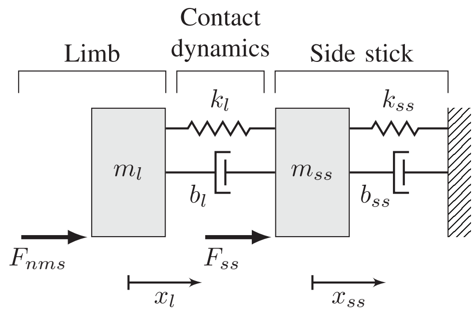


Fig. 2. Schematic representation of the lumped limb and stick dynamics

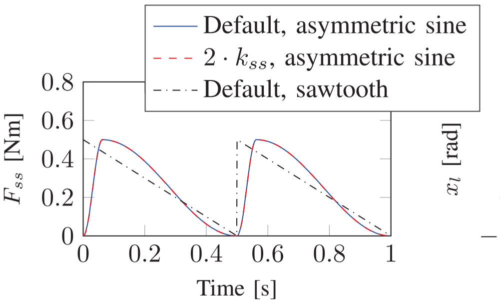
The lumped state-space matrices, (1) and (2), contain four states (side-stick position and velocity x_{ss} and $\dot{x}_{ss}$; limb position and velocity x_l and $\dot{x}_l$), two inputs (neuro-muscular force F_{nms}; force on the side-stick F_{ss}), and three outputs (side-stick and limb positions; contact force F_c which is the combination of the side stick and contact dynamics).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-k_{ss}-k_l}{m_{ss}} & \frac{-b_{ss}-b_l}{m_{ss}} & \frac{k_l}{m_{ss}} & \frac{b_l}{m_{ss}} \\ 0 & 0 & 0 & 1 \\ \frac{k_l}{m_l} & \frac{b_l}{m_l} & \frac{-k_l}{m_l} & \frac{-b_l}{m_l} \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 & 0 \\ \frac{1}{m_{ss}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{m_l} \end{bmatrix} \tag{1}$$

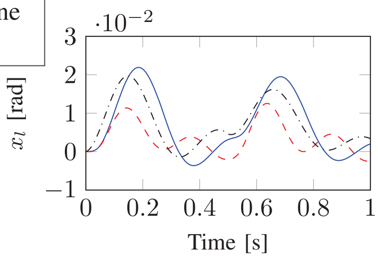
$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ k_l & b_l & -k_l & -b_l \end{bmatrix} \quad \text{and} \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{2}$$

To investigate effects of the side-stick dynamics, and the importance of specifying all parameters in scientific publications, an asymmetric sinusoid as described by Tappeiner et al. is applied (amplitude 0.25Nm, frequency 2Hz, offset 0.25Nm, asymmetry -1.5) to the system described before, and a system where the side-stick stiffness is doubled ($k_{ss_2} = 2 \cdot k_{ss} = 71.36$Nm/rad). The forcing functions for both systems are shown in Fig. 3(a). From the resulting limb position, Fig. 3(b), it can be seen that it is approximately *halved* when doubling the stick stiffness. The contact force, Fig. 3(c), shows that equal magnitudes are obtained, yet frequency content differs.

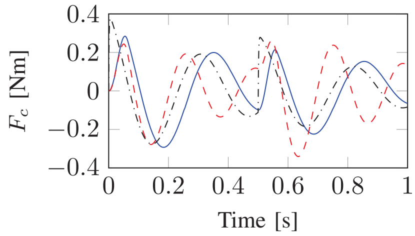
A full analysis of the effects of side-stick dynamics on the resulting observations to the pilot is beyond the scope of this paper. Clearly, they play an important role in the design of haptic feedback systems. The side-stick properties used in remainder of the paper are as described with the first system.



(a) Forcing functions used (F_{ss})



(b) Side-stick position (x_{ss})



(c) Contact force (F_c)

Fig. 3. System responses to an asymmetric input

B. Vibration specification

With the side-stick defined, the forcing function is designed. Both asymmetric-in-amplitude and -in-time have shown to be beneficial for perceiving direction, and a combination could perhaps be used. An example is the input illustrated in Fig. 3(a), which is asymmetric-in-time due to the difference in rise and fall time, *and* asymmetric-in-amplitude due to the positive offset resulting in only positive added forces.

The signal frequency and level of (a)symmetry are heuristically determined by changing the settings in the simulator and striving for best noticeable direction by the experimenter. The final settings are a frequency of 2Hz and an asymmetry of -1.5, following the definitions used by Tappeiner et al. Next, the stick dynamics are taken into account to further simplify the forcing function design: a sawtooth-shape was found to have a similar effect as the (slightly more complex) asymmetric sinusoid, see Fig. 3 (black and blue lines).

Fig. 3(a) shows that the asymmetric sinusoid is a smooth function, and the sawtooth contains a discrete step at each start of an 'oscillation'. Nevertheless, the stick dynamics filter this input, see e.g. the resulting limb position (Fig. 3(b)) and contact force (Fig. 3(c)) with similar results for both forcing functions. In the remainder of this paper, the sawtooth-shaped function is used. To compare it with a signal that is only asymmetric in amplitude, we will compare it with a triangular pulse (see Fig. 1(b)) used in automotive applications.

III. Method

The experiment was approved by the TU Delft Human Research Ethics Committee, and all eight participants (ages $\mu = 30$, $\sigma = 9$ years) signed an informed consent form. No participant reported a medical condition that limited sense or use in the hand they used to hold the stick. There were both left- and right-handed participants. Handedness should not be a determining factor, as pilots in the cockpit are controlling either as pilot-in-command (left seat, side-stick at their left) or co-pilot (right seat, side-stick at their right) position, regardless of their preferred hand.

A. Apparatus

TU Delft's Human-Machine Laboratory was used as shown in Fig. 4, which features a custom-made, hydraulically driven, *simulated* side-stick, located at the right-hand side. To the left, a throttle quadrant is present, of which a toggle-button is used to let the participant input a direction after each trial. In front of the participant a display is placed (Fig. 5) to request an input on the side-stick, a timer, an indication of the buttons, and a stop bar when a staircase is finished. Stick properties are tuned to match an Airbus-type stick ($m_{ss} = 0.2$kgm^2, $k_{ss} = 35.68$Nm/rad, $b_{ss} = 0.4$Nm/rads); this ensures that results are transferable to our main application. [5]

Fig. 4. Simulator inside view showing the throttle quadrant (left), screen (front), and side-stick (right)

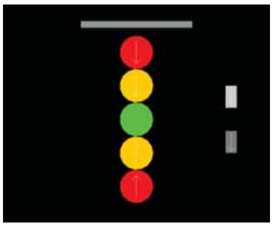


Fig. 5. Display provided to the participants; the traffic light indicates the required input change by the participant and is shown in the 'start'-phase, the right arrows show which direction is selected during the 'wait for input'-phase, and the top bar indicates the time in one run

B. Independent variables

The experiment aimed to obtain a threshold magnitude of the forcing function for which a pilot can indicate the direction while actively controlling the side-stick. Therefore the participants are asked to exert a force on the side-stick equal to the force required to deflect an Airbus side-stick 0.1rad in pitch (3.57Nm). The deflection is chosen as pilots in our previous experiment were, even in emergency scenarios, controlling mostly within 0.1rad deflection. [6] As the forcing function should be felt when the pilot is pulling, pushing, or not actively using the side-stick, the experiment is performed when the pilot is exerting negative (NEG, -3.57Nm), positive (POS, 3.57Nm), and no force (NO, 0Nm) on the side-stick.

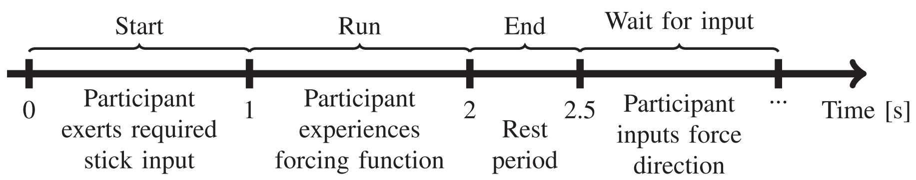


Fig. 6. Summary of the phases in one trial

Previous research has shown that operators manipulating a side-stick are more sensitive to differences in forces compared to positions, therefore the main analysis will be at one position (FORW, 0.1rad forward) and with the three force levels. [9], [10] To validate this assumption, one forcing function is additionally tested at zero neutral position (MID) with no force and with back force resulting in -0.1rad deflecting (AFT). If the assumption is indeed valid that the threshold is mainly determined by our sensitivity to force and far less by position, the comparison of the results should show similar thresholds.

Two forcing functions are selected to determine their respective threshold: a sawtooth (SAW) and a triangle (TRIANGLE) shape with a frequency of 2Hz. Only the former is used to analyze the assumption on the position and force interaction.

This makes in total 8 conditions (2 forcing functions $\times$ 3 force levels at 0.1rad, and the sawtooth function at the middle position with no force and -0.1rad).

C. Procedure

Several 'trials' are performed where a single forcing function is presented. Trials consist of three phases, see Fig. 6. In the first phase the 'traffic light' display is shown, Fig. 5 helping participants apply the proper offset force. After a full second of proper offset force, the run phase is started, during which the vibration signal is applied. An end phase without vibration, of $0.5s$ closes off the trial. Participants can then, with their left hand on the toggle button, indicate in which direction the vibration input was felt.

A staircase procedure is performed: after the participant experiences a cue, he/she is asked whether a change was observed, i.e., one 'trial'. The magnitude of the cue is decreased on a correct answer, and increased on an incorrect one. [11] The starting magnitude is so large that all participants start with a correct answer; the decrease in magnitude converges to the limit where the participant is able to sense a change. To improve staircase accuracy, following the first incorrect answer the amplitude increases on each incorrect answer and decreases following two consecutive correct answers.

The event of switching from a correct to an incorrect answer, and vice versa, for a staircase is called a *reversal*. Step sizes are determined by how many reversals have passed, the decrease is 30% for the first three reversals, 15% afterwards; the increase is 60% for the first three reversals, 30% afterwards, where the percentages are calculated based on the current magnitude. A staircase is completed when seven reversals are encountered.

Our experiment differs with respect to a 'standard' staircase application: for every condition mentioned with the independent condition, *two* staircases are performed in parallel. One staircase looks for the threshold where a participant can correctly indicate a direction for *positive* forcing functions (representing a pushing cue), one staircase looks for the *negative* threshold (pulling cue). The trials presented to the participant are a mix of the two staircases. Whether the direction of the next cue is positive or negative, is randomly chosen from a binomial distribution. Random directions are selected until *both* staircases had seven or more reversals.

The entire experiment for one participant lasts about 1.5 hours. After an initial safety and experiment briefing, a training is performed in which the participant is given feedback on his/her answer. This training is at least four runs with the sawtooth function and four with the triangle shape, and is concluded when the participant feels confident with the procedure. Following this, the above-mentioned eight conditions are executed following a randomized Latin-square design, ensuring that all transitions of conditions are distributed over the participants, where one condition lasts about five minutes. Between each condition a small break is held, and after four conditions a larger break is added.

D. Dependent measures

Each condition results in two threshold values for the forcing function force amplitude. These are calculated by averaging the last four reversals of a single staircase. In the following, a pushing/positive threshold is coded with 'UP', a pulling/negative threshold 'DOWN'.

Statistical analysis is performed using the R-programming language (packages 'PMCMR' and 'PMCMRplus', defining the p-value and test statistics (χ^2 and V)).[1]

E. Hypotheses

We aim to determine the most effective asymmetric vibration shape, its advised magnitude, and whether it depends on the side-stick position or force exerted on the side-stick. Results are expected to follow four hypotheses:

1) The threshold force where a direction can be indicated of the sawtooth-shaped forcing function is lower compared to the triangle-shaped one. This is due to the sawtooth-shaped being asymmetric in both time *and* amplitude, whereas the triangle is only asymmetric in amplitude.
2) The threshold force where a direction can be indicated of any forcing function is lower in the opposite direction from the force exerted by the participant. This because opposite direction from the force exerted has a lower background force, hence following Weber's law.

[1]Available using respectively https://cran.r-project.org/web/packages/PMCMR/PMCMR.pdf and https://cran.r-project.org/web/packages/PMCMRplus/PMCMRplus.pdf.

3) The threshold force where a direction can be indicated is lowest, and equal for pulling and pushing cues, when exerting no force on the side-stick. As background forces are equal, this follows again from Weber's law.
4) The threshold force where a direction can be indicated depends on the force applied, not on stick position. As perception research showed operations to be more sensitive to differences in forces compared to positions.

IV. Results

An example of the result of a single staircase is shown in Fig. 7. The structure of the staircase is especially visible in the negative one: initially each correct answer decreases the amplitude. After the first incorrect answer, two consecutive correct answers are needed to decrease again. Note that after the fourth reversal, the step size is decreased.

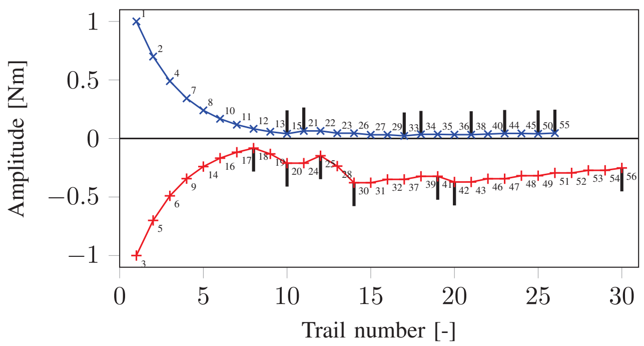


Fig. 7. Example staircase-procedure (Participant 3), when applying a backward force on the stick and using a triangular pulse; numbers next to the points indicate the trials' sequence, vertical lines indicate reversals

The resulting JND levels for all participants over all conditions are illustrated in Fig. 8. Note that the coding of the conditions is as given in Subsection III-B. Some general trends can be observed: first, the spread in JND values for TRIANGLE are much higher as compared to those from SAW. Second, the JND values for TRIANGLE are higher. Third, differences in JND for pushing and pulling forces (UP versus DOWN) while varying the force applied by the participant (POS/NO/NEG) seem to be present for both forcing functions, yet are more visible for TRIANGLE. Fourth, the absolute maximum median JND value found for SAW is 0.094Nm.

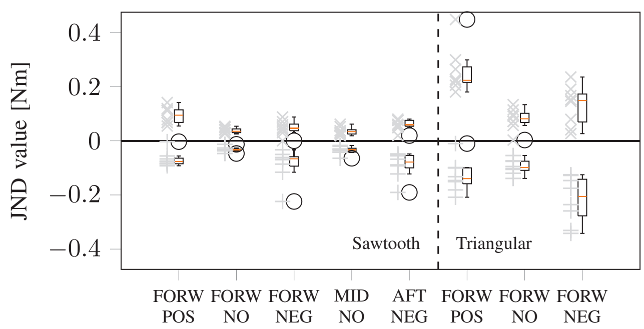


Fig. 8. Boxplots of the JND values obtained for all conditions, circles indicate outliers, crosses indicate points for pushing cues, plus-signs for pulling cues

Statistical analysis of all forward-positioned cues (FORW) using a Friedman Rank Sum Test showed that there are significant changes between conditions ($\chi^2(11) = 63.1$, $p < 0.001$). Further investigation in the differences was performed with pairwise comparisons using Conover's test, for which the Bonferroni corrected p-values are shown in Table I.

A final statistical analysis to investigate the position effect was done: a paired Wilcoxon test to compared the JND values found for forward position with no force (SAW/FORW/NO) with middle position (SAW/MID/NO), separately for the pushing and pulling forces, as well as for forward position with backwards force (SAW/FORW/NEG) and backwards position (SAW/AFT/NEG). These tests show that there is no statistically significant change (for all $p > 0.37$). In more detail, comparing no force forward and mid positions for pushing cues gives $V = 23$ and $p = 0.55$, for pulling $V = 24$ and $p = 0.46$; with the participant pulling on the side-stick and comparing forward and aft positions for pushing cues $V = 11$ and $p = 0.38$, for pulling $V = 18$ and $p = 1$.

V. Discussion

Considering the first hypothesis, a comparison needs to be made between the sawtooth and the triangle signals. Especially comparing the p-values indicated in Table I by subscripts 1, equal conditions (same force applied, and same forcing function direction) can be compared. These tests show that there is a clear difference between both forcing functions except for the NO/UP and POS/DOWN conditions. The differences can also be seen from Fig. 8: a decrease for the sawtooth-shape can be verified, together with a decrease in variation. This supports the hypothesis of decrease in threshold force when using the sawtooth-shape function instead of the triangle-shape.

For the second hypothesis we consider the individual conditions (forcing function TRIANGLE or SAW, force level POS or NEG) and compare the UP and DOWN values. Fig. 8 shows a difference for the triangular-shaped function: a positive force by the participant (POS) results in a higher positive JND and visa versa; for the sawtooth-shaped functions this is less evident. Participants seem to be more sensitive to forcing functions in the opposite direction of the force applied. Studying the p-values indicated by subscripts 2 in Table I this observation is not significant. Because of the small sample size and conservative statistical tests, the lack of significance is not considered sufficient to reject the hypothesis either.

The third hypothesis requires no (statistically significant) change between the UP and DOWN thresholds when the participant is applying no force on the side-stick (NO). Looking at the FORW/NO conditions for both forcing functions gives a visual confirmation that this is indeed the case. The p-values indicated by subscripts 3 in Table I confirm this with clear statistical significance, hence supporting the third hypothesis.

The fourth and last hypothesis compares the results of the sawtooth-shaped forcing function for different positions. Visually comparing the results for the no load at forward and mid positions, and negative load at forward and aft positions, only small changes are observed. Wilcoxon tests showed

TABLE I

p-VALUES FOR POST-HOC PAIRWISE COMPARISONS (CONOVER'S TEST, BONFERRONI CORRECTION), ROUNDED TO TWO DIGITS; SUBSCRIPTS IN TEXT

			SAW						TRIANGLE				
			NEG		NO		POS		NEG		NO		POS
			DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP	DOWN	UP	DOWN
SAW	NEG	UP	1.00_2										
	NO	DOWN	0.07^{*}	1.00									
		UP	0.26	1.00	1.00_3								
	POS	DOWN	1.00	1.00	0.14	0.47							
		UP	1.00	0.47	0.01^{***}	0.04^{**}	1.00_2						
TRIANGLE	NEG	DOWN	0.00_1^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.03^{**}					
		UP	1.00	0.01_1^{***}	0.00^{***}	0.00^{***}	1.00	1.00	1.00_2				
	NO	DOWN	1.00	0.05^{**}	0.00_1^{***}	0.00^{***}	1.00	1.00	0.26	1.00			
		UP	1.00	1.00	0.07^{*}	0.26_1	1.00	1.00	0.00^{***}	1.00	1.00_3		
	POS	DOWN	1.00	0.01^{**}	0.00^{***}	0.00^{***}	1.00_1	1.00	0.84	1.00	1.00	1.00	
		UP	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00_1^{***}	1.00	0.35	0.05^{**}	0.00^{***}	0.19_2

* indicates $p < 0.1$
** indicates $p < 0.05$
*** indicates $p < 0.01$

no statistical significance. Hence all evidence supports this hypothesis: a participant is more sensitive to the amount of force applied compared to the position of the side-stick.

Note that the side-stick properties were designed to resemble Airbus sticks as close as possible – to allow for quick implementation in practice, our participants were not real pilots. However, there is no reason to believe that pilot JNDs will be different and we can assume that better averages can be found with a higher number of participants.

These results can be directly used on the side-stick in the cockpit of an Airbus A320 and A330, and can be extrapolated to cars and other vehicles which are controlled using a side-stick. Additionally, the methodology can be used to determine similar properties for a control column, used in some other aircraft types, as well as other control devices.

Note that our participants only focused on the force they had to exert on the side-stick as well on the direction they perceived. In the intended application, pilots are actively operating the aircraft with a more specific task, for example flying an approach. Pilots are not fully focused on what he/she feels through the haptic feedback and the resulting threshold force is higher. When implementing a forcing function as researched here, a safety factor should be applied to make sure the pilot is feeling the force. A more time-consuming approach to circumvent this issue is a new experiment where the participants' focus is actively drawn away from the haptic feedback, yet a similar threshold task is performed in parallel.

An issue surfaced during this experiment, which is applying two parallel staircases: one participant's strategy was to input 'forward' whenever a pushing force was felt, and in *any* other case, whether nothing was felt, or the cue was not clear, a 'backward' input was given. This resulted in a good approximation of the threshold in the forward direction, whereas the backward direction approaches zero without any reversals. As the threshold values determined by the reversals assume a stochastic element in both staircases, results became invalid, the participant was removed and another one invited. To circumvent this problem, one can instruct participants to 'indicate direction, if not sure pick random input'.

VI. CONCLUSIONS

We investigated the perceivability of asymmetric haptic force cues designed to indicate *direction*. Results show that a sawtooth-shaped signal has a lower threshold and is recommended. When participants applied different force levels on the stick, data indicate a lower threshold for cues *opposing* the applied force; a non-significant effect. In case no force is applied on the stick, the threshold is equal in fore/aft directions. Participants were more sensitive to forces as compared to positions. The findings allow asymmetric-in-amplitude *and* -in-time vibrations to provide pilots with a clear direction cue – presumably also when actively controlling their aircraft.

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