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Aircraft Engineering and Aerospace Technology  
2020, vol. 92, iss. 9, pp. 1407-1412

ISSN: 1748-8842

DOI: <https://doi.org/10.1108/AEAT-12-2019-0265>

Accepted manuscript

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Final version available from <https://www.emerald.com/insight/content/doi/10.1108/AEAT-12-2019-0265/full/html>

# Pilot-Aircraft Haptic Feedback Tests

Accepted version of manuscript

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## Abstract

**Purpose** – this work leads to an improvement of pilot-aircraft interaction. The goal of the performed tests is an assessment of haptic feedback which mediates flight parameters to the pilot. Pedals indicate sideslip angle by vibrations and a sliding element inside the control stick is able to continuously indicate both angles of attack and sideslip.

**Design/methodology/approach** – the haptic feedback applied on rudder pedals and the control stick were tested on a flight simulator and flight tests in a couple of tasks. Pilot workload, readability of feedback and sideslip during turning flight were evaluated.

**Findings** – haptic feedback was assessed as a useful instrument for aircraft control. The feedback settings were perceived individually. Haptic feedback slightly improved sideslip during turning in a flight test but the results are not statistically significant.

**Practical implications** – the tests give promising results for human pilot performance. The training phase and personal settings of haptic feedback is a way to the improvement of human pilot performance.

**Originality/value** – the designed and tested device is a unique tool for improving pilot-aircraft interaction. The paper brings valuable experiences from its flight simulator and in-flight tests.

**Keywords** Flight simulator, Flight test, Haptic feedback, Pilot-aircraft interaction

**Paper type** Research paper.

## Introduction

The performance of human pilots recently lags behind autopilots and birds. What is the reason that computers and nature are better in flight-control than a man? A Pilot-Aircraft interaction is the weakest chain segment of aircraft control. The

pilot-aircraft interaction is connected to all accidents of small aircraft caused by a human factor. Birds feel aerodynamic characteristics of flow around their wings naturally as a man feels the ground while walking. Autopilots are fed by flight parameters many times every minute of flight. Both birds and autopilots control flight with permanent knowledge of flight parameters such as speed or dynamic pressure, angle of attack and altitude. A pilot can read all parameters on the instrumental board but it is out of the human ability to perceive and process all-important values during critical phases of flight. Aircraft give some feedback which pilot feel without conscious instruments checking such a control stick force or aircraft structure vibrations but this feedback is not sufficient. That shows aircraft accident statistics (EASA 2018, NTBS 2017) where the loss of control and the human factor are still the most common accident reasons in the general aviation sector.

The literature survey shows (Zikmund, 2018) that the current pilot-aircraft interaction methods have limitations. Visual sense might be overloaded in some flight phases. Mentioned research suggests transferring some pilot stimuli to the haptic sense. The device which mediates flight parameters to a pilot by the haptic way was designed and tested within this paper. The goal is to improve pilot performance in the case of small aircraft without an autopilot. The device consists of active elements at the control stick and rudder pedals. Angles of attack and sideslip are mediated to a pilot by vibrations of rudder pedals and movements of a sliding element mounted in a control stick handle. The device has been tested at a flight simulator first (n=12) and afterwards in a flight (n=1). This paper brings the results of both experiments.

## **Related work**

Haptic technologies are in the scope of researchers dealing with airliners cockpits recently. One of the current research topics is the design of a haptic feedback (HF) system for flight envelope exceeding protection (Baelen, 2018). HF is supposed to help a pilot control aircraft safely near the borders of a flight envelope. (Prinet, 2016) introduced a tactile spatial guidance method for collision avoidance. (Castillo, 2016) adverts to the importance of free-eyes pilot-aircraft interaction. Morphable and interactive controls are expected in a future aircraft cockpits. Research of the pilot-aircraft interaction needs a good human pilot behaviour model. Such a model with visual and tactile cues perceived from the pilot-aircraft interface is presented by (Xu, 2019). The segment of general aviation aircraft has different demands from haptic technologies. (Beefting, 2018) shows that HF significantly increases both primary and secondary task performance of the pilots. Workload ratings are significantly lower, and head-up time increases with HF at the same time. (Nieuwenhuizen and Bülthoff, 2014) applied the HF in personal aerial vehicle control simulation. They simulated a highway in the sky display with a goal to create an easy to use control interface for non-expert pilots. All mentioned resources are connected with topics of pilot's workload decrease and eyes-free pilot-aircraft interaction. According to (Brock, 2015), using multiple

modalities can break down the complexity of communicated information. (Loomis, 2012) describes various approaches for sensory substitution of vision from the perspective of cognitive science and neuroscience.

## Flight Simulator test

To assess the possible effects of the HF system on pilot performance prior to flight tests, a flight simulator test was prepared. Simulator software consisted of an X-plane 11 PC flight simulator and hardware composed of a joystick and rudder pedals equipped with haptic devices as shown in Figure 1. A sliding element was built in the joystick. The sliding element mediated AoA and AoS by symmetrical and unsymmetrical movement out of the handle surface. A range of the sliding element displacement is 8 mm and is powered by two servos with power about 2x20 N. It has also a shaker function near stall flight conditions. The rudder pedals provide a pulsating vibrations when a sideslip exceeds a threshold value. The pedals vibrate at the same side where a pilot reaction is needed to decrease aircraft sideslip. The vibration motors induce vibrations of frequency 230 Hz  $\pm$ 10% and amplitude 7g  $\pm$ 10%.

**Figure 1 Flight simulator testing setup and rudder pedals.**



Twelve people with a piloting license took part in the flight simulator experiment. Before the experiment itself, participants were given time to become familiar with the flight simulator itself and afterwards with the haptic devices. The Cessna 172 flight model was used during the experiment.

The first part of the experiment required the pilots to fly three times through the set of gates forming a test track at low altitude above water level at a given range of airspeed. Each flight was conducted with a different configuration of haptic devices. One flight was with HF off, another one was with AoA feedback and AoS on the joystick feedback turned on and the last one was with the AoA feedback and AoS on the rudder pedals turned on. The sequence of these flights was assigned to each pilot by the Latin square method. Pilots were requested to fly at low airspeed and with a minimal angle of sideslip. There were no instructions about checking the turn indicator. The goal was to let pilots fly as they are used to.

The second part of the experiment required the pilot to perform a takeoff and climb out. During the climb, the engine was made inoperable by the experiment control script without prior notice to the pilot who was then required to get the aircraft on the ground safely. Half of the participants performed this task with HF the other half without HF.

During the experiment, participants filled the questionnaire concerning their perception of feedback, information clarity, helpfulness, unambiguity, etc. Assessment of the experiment includes evaluation of questionnaire answers and evaluation of flight data.

### Questionnaire assessment

Participants assessed their workload during each flight on scale 1(low) - 3(high). Their answers were averaged for flights without HF, with HF AoS on a joystick, with HF AoS on rudder pedals respectively: 1.75, 2.33, and 2.08. The workload during flight without HF was assessed the lowest that might be caused by insufficient training for the HF system. Intensity, unambiguity, and helpfulness of information given by HF system were assessed for flights with active HF on scale respectively: 1(too low) - 5(too high), 1(no) - 5(yes), 1(poor) - 5(high) both for information on AoA and AoS. The answers were averaged among the participants and are shown in the Table 1.

**Table 1 Questionnaire results.**

The flight using HF both AoA and AoS on joystick sliding element			
	Intensity	Unambiguity	Helpfulness
AoA	2.92	3.92	3.25
AoS	2.58	3.42	3.42
The flight using HF of AoA on joystick and AoS on rudder pedals			
	Intensity	Unambiguity	Helpfulness
AoA	2.92	4.67	3.67
AoS	2.67	2.75	3.5

For evaluation of flight data cumulative sideslip angle was calculated for each flight of each pilot to measure their performance. The cumulative sideslip angle is dimensionless value taking aircraft sideslip and time during which the aircraft was experiencing the sideslip into account. It was expected that pilots will achieve lower cumulative sideslip in flights with active HF. T-tests were conducted to test the null hypothesis that mean values of cumulative sideslip are identical. Both flights with HF active were compared to flights with HF inactive. The null hypothesis was not rejected on a 95% confidence level in both comparisons. Therefore the HF in this test has no positive nor negative effect on the pilots' ability to fly with minimal sideslip. The answers in the questionnaire were compared with flight data using correlation coefficients. The correlation matrix is shown in the Table 2.

**Table 2 Correlation matrix of the questionnaire and simulator test results.**

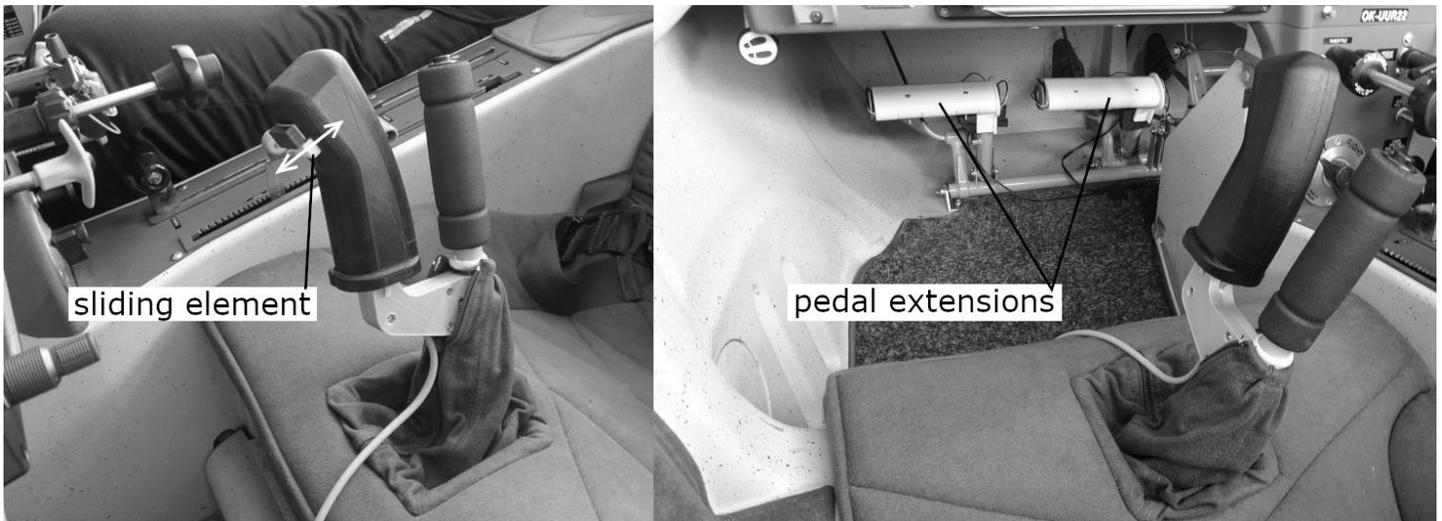
Correlation matrix, confidence level 90% (alpha = 0.1)							
Sideslip HF off	Sideslip AoS joystick	Sideslip AoS pedals	Pilot age	Real flight hours	Flight sim. hours	HF asist, AoS joystic	HF asisit. AoS pedals
[-]	[-]	[-]	[years]	[hrs]	[scale 0-2]	[scale 1-5]	[scale 1-5]
1	0.8668	0.4113	-0.0032	-0.1893	-0.6273	0.2551	-0.1386
0.8668	1	0.5613	-0.2316	-0.3087	-0.5951	0.2565	-0.2705
0.4113	0.5613	1	0.3209	-0.1021	-0.6557	-0.0997	-0.4832
-0.0032	-0.2316	0.3209	1	0.5294	-0.2099	-0.5995	-0.2435
-0.1893	-0.3087	-0.1021	0.5294	1	0.4007	-0.3997	0.0673
-0.6273	-0.5951	-0.6557	-0.2099	0.4007	1	0.1159	0.1611
0.2551	0.2565	-0.0997	-0.5995	-0.3997	0.1159	1	0.1473
-0.1386	-0.2705	-0.4832	-0.2435	0.0673	0.1611	0.1473	1

The correlation matrix shows a weak correlation between pilots' assessment of HF helpfulness and sideslip flight data result. The pilots who assessed the helpfulness of HF with AoS indication on joystick better had worse cumulative sideslip in practice. While pilots who assessed the helpfulness of HF with AoS indication on pedals better truly had lower cumulative sideslip in practice. There is also a strong correlation between flight sim hours of participants and cumulative sideslip during all flights. That shows a high dependency of the experiment result on flight simulator environment and experiences in general.

### Flight test

This chapter and partially the discussion chapter contains text published at EASN conference (blinded) where the flight test was described in a more detailed way. For the flight test, it was necessary to create new haptic pedal extensions because pedals in the WT-9 Dynamic aircraft used for experiment have different construction than pedals used with the flight simulator. The pedals are shown in Figure 1 and Figure 2. The behaviour of the system was simplified relatively to flight simulator test. The AoS threshold has fixed value and is not changed with aircraft speed in the flight test variant. The reference element marking the maximal AoA sliding element position was added to haptic joystick and the shaker function of the sliding element was removed. The system was operated by a control unit based on Arduino Mega 2560 with a data logging function. Sampling frequency was 10 Hz. Flight data were acquired from vane sensors and accelerometer and saved to an SD card in the control unit. There was no filtering of the vanes signals. The vanes showed to be sufficiently stable in the airflow. Analog signals of AoA and AoS were converted to digital with 10-bit resolution per 360 degrees. The acceleration data has not been used for control of the haptic feedback system. The accelerations were used only for turn's identification in the post-processing of flight data record.

**Figure 2 Haptic feedback actuators for the flight test.**



The flight test of the HF system consisted of a pilot's subjective assessment, and data collection during 360 degrees turns. The subjective assessment aimed to inflight verification of the HF by a test pilot. This task was repeated at various speeds within the range between a safe near-stall and the maximal speed. The pilot commented intensity and readability of rudder pedals vibrations in sideslip flight. There were two issues to be checked. The first was possible spreading of vibrations from one pedal to the opposite pedal. The second issue was interference between natural aircraft vibrations and vibrations of HF. Positions and function of the sliding element on the control stick were tested at the same speeds as vibrations of rudder pedals.

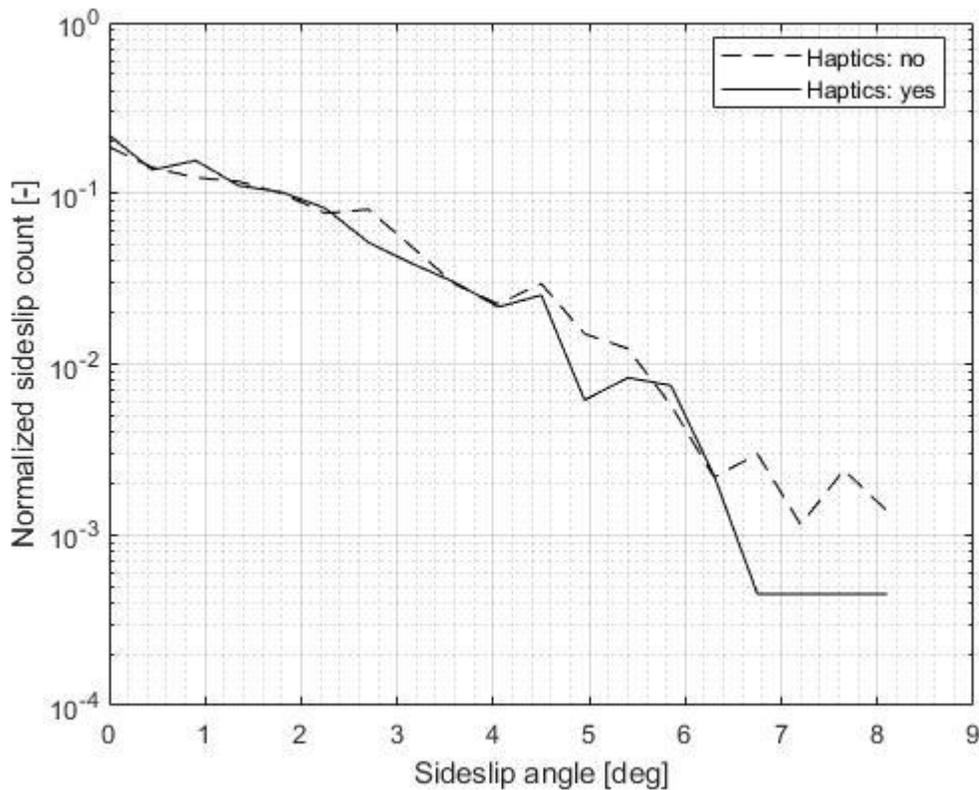
The second task was 360 degrees turns. The turns alternated left and right. One half was flown without the HF and the second was with the HF. The HF was alternately switched on and off each second turn to mitigate the learning effect. AoS was measured as a parameter for the HF system evaluation. Two hypotheses were tested. The first that HF decreases the mean value of the sideslip angle during turning. The second that HF decreases the sideslip angle above the vibration threshold, which was set up to 5 degrees.

## **Results**

The HF system was subjectively assessed in horizontal straight flight at first. The range of AoA was 7 to 19 degrees. The angle was measured from an estimated horizontal aircraft axis. The speed range was from 80 km/h to 180 km/h. The sliding element was described by the pilot as well sensible with changes in AoA but with continuous wobbling movement that was rather disturbing. Vibrations of rudder pedals activated when onboard sideslip indicator shows half of the ball out of the bracket at the cruise speed. The pilot commented vibrations as well as sensible and sidewise unambiguous, even better than on the flight simulator with a similar HF system. Tilting movement of the sliding element during sideslip flight was assessed as considerably worse than the one of vibrating pedals. That confirmed the fact that unsymmetrical HF on a control stick is better for roll guidance than for yaw guidance.

Twelve horizontal turns were performed on the indicated airspeed 140 km/h. 6 right and 6 left turns were flown in a swapping order with and without haptic feedback. The mean sideslip angle was evaluated in the following way. The angle of sideslip range was cut into short intervals. Counting of absolute value of sideslip angles duration for each interval gave its distribution. The distribution was normalized by dividing of the total duration of the measured record for each turn. That means the areas under the curves in the Figure 3 are equal to one. This normalized distribution of sideslip angle was evaluated for each turn separately and for combined groups of turns with and without haptics, see Figure 3.

**Figure 3 Normalized sideslip angle distribution in turning flight.**



The mean angle of sideslip was counted as a center of gravity of the area under the normalized sideslip distribution. The mean sideslip angles were compared by the one-tailed t-test. Mean values of sideslip angles in the turns without haptics is ( $M = 1.86$  deg,  $SD = 0.78$  deg) and in turns with haptics is ( $M = 1.66$  deg,  $SD = 0.43$  deg). It means, that the difference is not statistically significant,  $t(10) = 0.54$ ,  $p = 0.30$ . The count of normalized flight duration when aircraft sideslip was greater than the given threshold 5 deg was evaluated after that. The duration when the sideslip was greater than the threshold was ( $M = 4.32$ ,  $SD = 6.06$ ) per cent of the total time without haptics and ( $M = 2.60$ ,  $SD = 2.84$ ) per cent of total time with haptics. That means, that haptics decreased sideslip angles above the threshold, but the difference is not statistically significant again,  $t(10) = 0.63$ ,  $p = 0.27$ .

## Discussion

The flight simulator tests pointed to strong inter-individual variations in the assessment of the HF. The correlation matrix in Table 2 brings some unexpected results. While pilots were not instructed on how to work with turn coordinator during the experiment, they were asked about their approach afterwards. One pilot stated he was using solely the HF system in both flights where it was active. Another pilot was using solely HF in flight with AoS HF indication on the joystick. These pilots performed with the highest cumulative sideslip, but they both were flying the unfavourable variant of Latin squares, where HF flights preceded the flight with inactive HF. Other participants were using turn coordinator even in flight with HF active and they have chosen different ways to combine available readings. Some of them were regularly checking the turn coordinator, others were using it only to verify their HF reading. Both groups agreed that HF increased their awareness of AoA and AoS, but training with the system was not sufficient for them to fully benefit from HF usage.

The sliding element of the control stick was described by the pilot as well sensible but with disturbing continuous wobbling movement during flight test.. That movement of the control stick sliding element was caused by the coarse digital conversion of AoA input. This fact influenced also the accuracy of sideslip qualitative assessment.

During the flight simulator test, some pilots doubted whether vibrations as HF are suitable for motorized aircraft. We were concerned that vibrations would interfere with the aircraft engine vibrations and that vibration of one pedal would spread to the other pedal devaluating the HF completely. However, vibrations of the haptic pedals were commented by the pilot as well sensible and sidewise unambiguous after the flight test in the whole range of tested speeds. That is an improvement in flight test compared to the flight simulator test. The flight simulator rudder pedals use parallelogram guidance of the pedals with a short mechanical link between both pedals. The aircraft used for the flight tests was equipped with T-shaped rudder pedals with a longer and less stiff mechanical link between both pedals. That combined with a change in treadles shape and therefore change in pedals attachments housing the vibration motor, lead to the improvement of directional sensibility of rudder pedal vibrations.

Tilting function of the sliding element was confusing for a pilot. Therefore the flight test was performed only with AoA signaling by the sliding element. Tilting movement of the control stick sliding element was concluded to be more suitable for a roll instead of yaw guidance. A pilot limb would be perceiving and acting in that case. Roll guidance by the tilting function of the control stick seems to be promising and should be analysed.

Quantitative evaluation of the HF benefit was tested on the aircraft sideslip during 360 degrees turns. The overall sideslip decreased in case of flight with the HF, but the improvement was not statistically significant. That is caused by a small statistical sample of twelve turns. The flight test was carried out by a single pilot. The flight simulator test pointed to string inter-individual differences in perception of HF. The test pilot did not complete training of using the HF system. He only had experience from two-hours flight simulator test, which he participated 5 months before flight test. Figure 3

presents normalized sideslip distribution in the course of twelve 360 degrees turns. There is a small decrease of sideslip with HF around the threshold of 5 degrees when the pedals vibrations were activated. It can be supposed that the decrease in the threshold value would help to decrease the sideslip during flight. The threshold level should be decreased only to an appropriate level. A too low value would lead to excessively frequent haptic information that would disturb a pilot during the flight with no further positive effect. The second assumption for the HF benefit improvement is a pilot training on usage of the HF system. The system was designed to be intuitive, but ongoing research shows a significant learning effect for this pilot-aircraft interaction method.

There is another space for the HF system improvement. Vanes for AoA and AoS were used in the flight test. These vanes are not suitable for common usage of the small aircraft because of their price and vulnerability during ground handling. Supposed solution for a commercially offered system of this kind is expected to include AoA pitot tube that uses only pressure measurements for AoA sensing and lateral accelerometer to substitute the AoS measurements by the acceleration measurements. Such hardware setup is recently used in avionics systems.

## **Conclusion**

In this paper, we described the results of the evaluation of novel pilot-aircraft interaction method based on haptic interaction. Our results indicate that it is possible to substitute part of the information typically perceived by the visual sense by haptic sense. The system capable of providing information about AoA and AoS comprises a sliding element embedded into the control stick and vibration elements mounted into rudder pedals. There are high inter-personal differences in subjective assessment of the system. The results of the experiments indicate that the system can decrease the sideslip angles, even in critical phases of a flight. However, the difference was not evaluated as statistically significant, mostly due to the relatively small sample size, high inter-personal variations and learning effect.

## **Further Work**

It is subject of the future work to improve the system to mitigate issues revealed during the evaluation. For instance, vibrations of the sliding element caused by quantization error will be resolved. Also, usage of the sliding element tilting for the indication of roll guidance should be investigated. Future experiments should involve a longer training period to mitigate the learning effect and investigate the effects of the system on pilots that are properly trained to use it.

## Acknowledgments

This research has been supported primarily by TACR, project no. TJ01000122 “Haptic feedback of assistant systems for flight safety improvement” and partially by the Research Center for Informatics project CZ.02.1.01/0.0/0.0/16 019/0000765.

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## Nomenclature

### Definitions, Acronyms and Abbreviations

AoA	Angle of Attack
AoS	Angle of Sideslip
HF	Haptic Feedback