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Pilot Evaluations of Augmented Flight Simulator Motion

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In an earlier paper it was proposed that the turbulence-induced motion of a flight simulator could be augmented without affecting the visual and instrument displays. This may be necessary if the simulator's washout filters severely restrict its motion response to atmospheric turbulence. The present study has implemented the proposed technique on the University of Toronto Institute for Aerospace Studies flight research simulator, and carried out pilot evaluations for both high-altitude and low-altitude operations in the presence of atmospheric turbulence. The results indicate that the technique can successfully increase the simulator's motion response to turbulence in a manner that is acceptable to pilots. It was found that a simple second-order transfer function representation of the aircraft is sufficient within the motion augmentation channel. The resulting motions were judged to add to the realism of the simulation and to compare favorably with other training simulators.

Introduction

IN Ref. 1 a technique for augmenting flight simulator motion response to turbulence was proposed. This article describes how this technique was implemented on a flight simulator and subjected to pilot evaluations.

The need for augmenting the motion response due to turbulence arises because the software (washout filters) used to drive the motion system is designed to produce realistic motion cues while restricting the resulting motion to remain within the physical limitations imposed by the ground-based motion hardware. When these motion-drive washout algorithms are tuned to accommodate pilot-induced motions they often have the undesired side effect of overly attenuating the heave response of the simulator to turbulence. It is shown in Refs. 1 and 2 that one need only consider the aircraft's heave response ($a_B^{\bar{z}}$) to the vertical component of turbulence (W_G) in order to compensate for this effect. The scheme devised to accomplish this is illustrated in Fig. 1.

The path from turbulence input to simulator motion can be seen in Fig. 1. Ignoring the augmentation system, the inputs to the flight equations of block 1 are the pilot's controls δ, and the turbulence T_1. The response of the flight equations to these inputs feeds the visual display (outside scene), the flight instruments, and the motion system. The goal of the present scheme is to augment the simulator's motion response to turbulence without interfering with the visual display and instruments. This can be achieved by generating a signal representing the aircraft's response to turbulence alone and then feeding it into the motion system in a suitable manner. Because the frequency content of motion signals due to turbulence overlaps substantially with that due to pilot control activity, it is not possible to separate the two effects through the use of filters on the output of the flight equations of block 1. The proposed technique for obtaining a signal representing the aircraft motion response due to turbulence is depicted in Fig. 1 by the augmentation system. Here, T_2 represents the turbulence input (which may be the same as T_1 or different depending on the designer's goals), and the flight equations of block 2 may be the same as those of block 1 or a simplified version of them. The output from the flight equations of block 2 is used to generate turbulence-related simulator motions by suitably adding it to the signals already present due to δ and T_1 coming from the flight equations of block 1. This is used to compensate for the undesired attenuation of the motion signal due to T_1 by the simulator's primary washout filters. In the present development the flight equations of block 2 are represented by a simplified transfer function relating the aircraft's heave acceleration response ($a_B^{\bar{z}}$) to W_G. $a_B^{\bar{z}}$ is used to augment the motion-drive signal coming from block 1.

The goals of the present study were to 1) confirm that augmenting the simulator motion will not result in exceeding the travel limits of the motion hardware when there is a pilot in the loop; 2) determine whether the proposed method of augmenting the simulator motion produces motion cues acceptable to pilots; and 3) obtain pilot evaluations of turbulence-induced motion cues over a range of conditions when employing the augmentation technique.

Aircraft Transfer Functions

The aircraft employed in the present tests was a structurally rigid B-747 implemented on the University of Toronto Institute for Aerospace Studies (UTIAS) flight research simulator (see Fig. 2). It was decided to evaluate the motion augmentation scheme for the aircraft in both a cruise and a landing configuration. For cruise, the aircraft was taken to be clean and in level flight at 295 kt indicated airspeed (KIAS) at an altitude of 21,000 ft. For landing, the aircraft was initially evaluated with 25-deg flaps and the landing gear down and flown in level flight at 170 KIAS at an altitude of 2500 ft.

Describing functions relating $a_B^{\bar{z}}$ to W_G were determined by using power spectral density measurements based on input

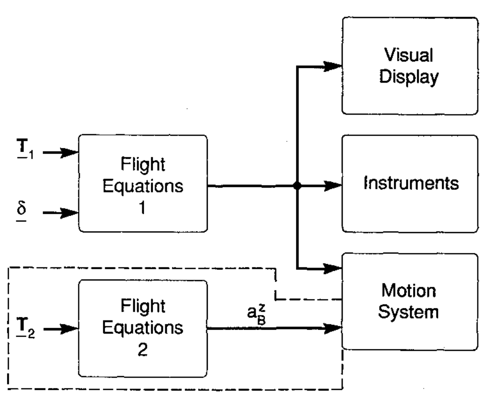

Fig. 1 Simulator system.

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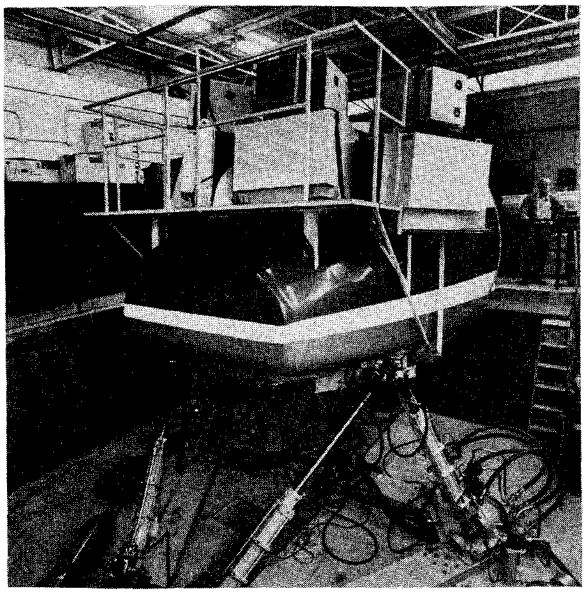

Fig. 2 UTIAS flight research simulator.

W_G and output a_B^z data produced while flying through the complete turbulence field. Bode plots were generated of the form

$$DF(\omega) = \frac{\Phi_{W_G a_B^z}(\omega)}{\Phi_{W_G W_G}(\omega)} \tag{1}$$

The resulting plots are shown in Figs. 3 and 4. As described in Ref. 2, low-order transfer functions were fitted to these plots. For the cruise case two second-order transfer functions $F1$ and $F2$ were generated. As shown in Fig. 3, $F2$ produced a much better fit to the data, particularly at the higher frequencies. For the landing case two second-order transfer functions $L1$ and $L2$ and a fourth-order transfer function $L3$ were generated. As shown in Fig. 4, $L3$ produced the best fit and $L1$ the worst. However, the increased complexity of the better transfer functions must be paid for by the extra time required to select their parameters and the computer overhead associated with their implementation in real time on the simulator.

Flight Conditions

The turbulence model employed was the $M1$ version developed in Ref. 3 which was judged to be the most realistic in pilot evaluations of several alternatives. It is based on filtered white noise modified to produce non-Gaussian turbulence. The turbulence model produces three uncorrelated gust velocities in the aircraft body-fixed reference frame. These are applied at the aircraft's c.g. Rolling and yawing gusts are generated and are combined with the aircraft rotational rates to represent the influence of spatial gust gradients. A gust pitching effect due to the horizontal tail is included by adjusting the tail angle of attack in response to a time delayed version of W_G.

Two flying tasks were employed when the evaluation pilots were assessing the turbulence-induced motion. The first was a loose formation flight in which the lead aircraft flew a racetrack pattern[2] as shown in Fig. 5. The lead aircraft was used as a means to guide the pilots through the same set of maneuvers. Turbulence was present during the complete run. The height for the flight was 20,700 ft above ground level (AGL) (with ground level being at 500 ft altitude) and the airspeed was 295 KIAS. The second task was the approach to landing depicted in Fig. 6. As shown in the figure, turbulence was present from part way through section 2 until that point in section 4 where the height goes below 500 ft AGL. Section 1 begins with the aircraft at 6000 ft AGL and

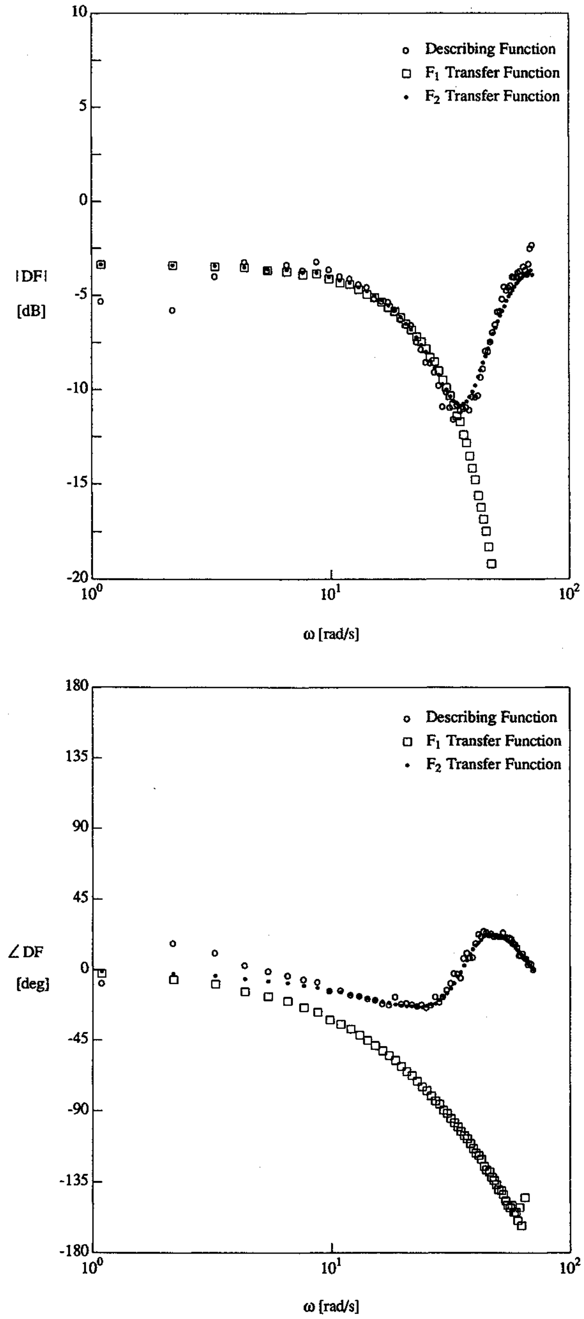

Fig. 3 Describing function for formation flight.

220 KIAS. The objective during this section is to decelerate to 170 KIAS and deploy 25-deg flaps and landing gear. In section 2 the aircraft descends to a height of 2000 ft AGL. Following a sidestep maneuver in section 3 an instrument landing system (ILS) approach is made in section 4.

Pilots

The five pilots participating in this study were either active airline pilots or active company pilots. All of the subjects took part on a voluntary basis. While the pilots were not previously experienced on the B-747, all were familiar with transport aircraft and had significant simulator experience. Table 1 outlines their flying and simulator hours.

Experimental Plan

The turbulence levels for the flying tasks were selected so that the turbulence augmentation technique generated a significant increase in heave specific force without causing the simulator to reach its physical travel limits. The motion drive algorithm employed was the classical washout CW2 of Ref.

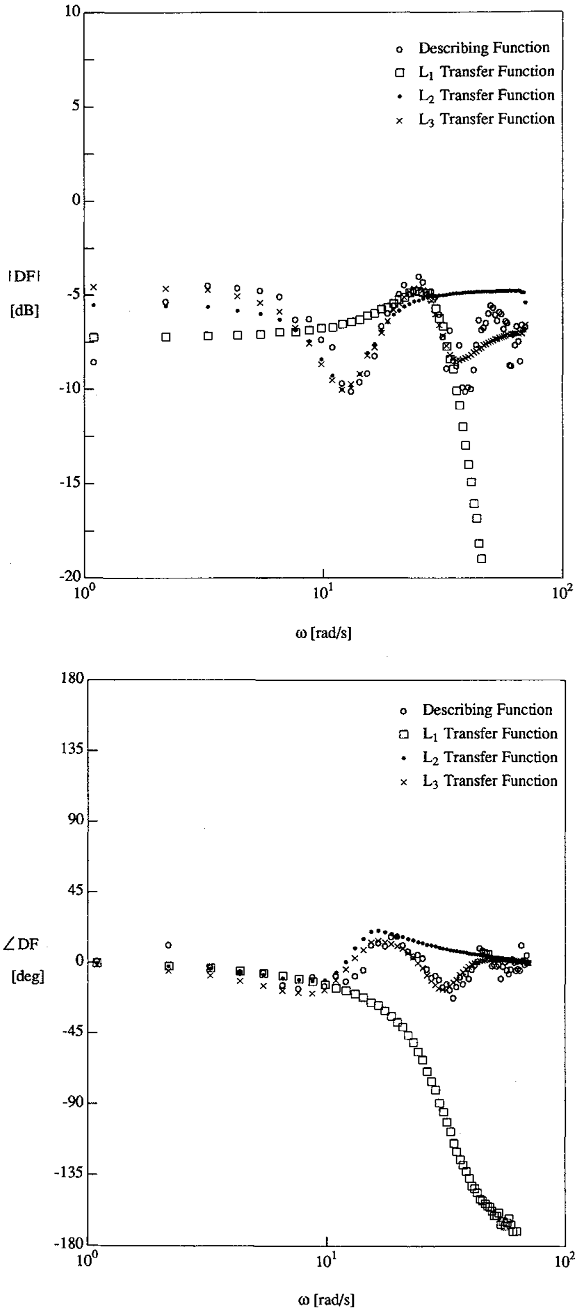

Fig. 4 Describing function for landing approach.

4. It was found that W_G for the landing task could be scaled up by a factor of 2 relative to that employed for the formation flight while still meeting the travel limits requirement. Typical plots of the standard deviation of vertical specific force in the simulator are shown in Fig. 7. It can be seen that the augmented cases produced approximately twice the nonaugmented levels.

Data were gathered for both complete single 10-min executions of the flight paths depicted in Figs. 5 and 6, and paired comparison trials were carried out using the indicated section in Fig. 5 and sections 3 and 4 of Fig. 6. Each of the latter flights lasted 4 min. Each of the above flights was flown without turbulence augmentation *NA* and with *F*1 and *F*2 augmentation for the formation task, and with *L*1, *L*2, and *L*3 augmentation for the landing task.

Each pilot participated in 2 days of training and data gathering. The formation task was flown on the first day and the landing task on the second. Each day began with task training using the full flight paths. They were allowed to continue to practice until they felt comfortable with the task. This was

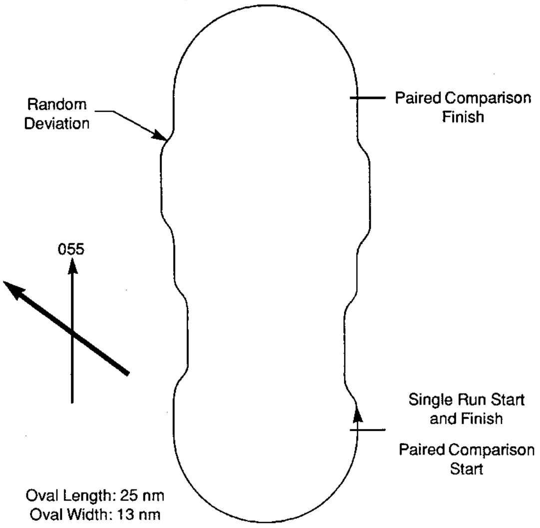

Fig. 5 Formation flying course.

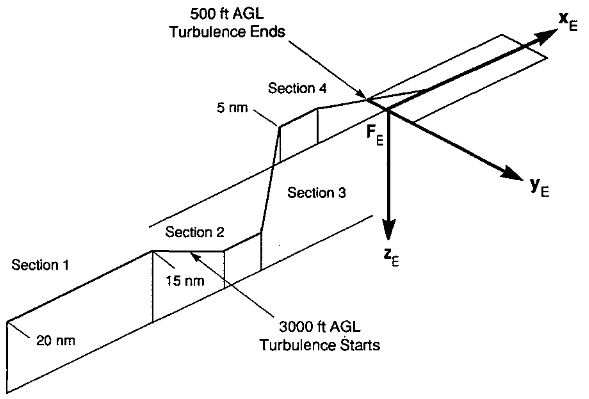

Fig. 6 Landing approach course.

followed by data gathering employing the full flight paths first and then the paired comparison tests using the shorter flights. Within each of these blocks each pilot tested all the turbulence treatment cases once in a randomized sequence.

The pilots answered a questionnaire at the end of each 10-min run and a number of performance and motion measures were made. The following questions from the questionnaire were directed towards the goals of the present study and are reported herein:

1) Did the turbulence add to the realism of the simulation?

2) Did the heave motion response to turbulence compare favorably to that experienced in heavy transport aircraft?

3) Did the heave motion response to turbulence compare favorably to that experienced in training simulators?

The object of the paired comparison tests was to obtain a ranking of the augmentation formulations. The pilots flew the same maneuver twice in a row with a different pair of turbulence treatments (including *NA*) in each set (3 pairs for the formation case and 6 pairs for the landing case). The ordering of the pairs was randomized and each pair was flown once by each pilot. Within each pair the pilot must indicate which turbulence treatment he felt best simulated the aircraft's response to turbulence. A ranking must be given in all cases, even if the treatments appear to be very similar. This generates a hierarchial ordering of the treatments, the validity of which can be checked by analyzing the internal consistency of each pilot's rankings, and the consistency among the pilots.

Experiment Results

An analysis of variance was carried out on the performance measures and it was determined that pilot performance was not influenced by the turbulence motion augmentation em-

Table 1 Pilot experience summary

Pilot	Current position	Flying hours	Transport hours	Simulator hours
1	F/O DC-9, 767	13,500	8,000	200
2	Pilot, dash 8	13,000	7,500	100
3	Pilot, dash 8	12,600	12,000	55
4	Capt. A320, 767	10,000	9,000	500
5	Pilot, dash 8	16,000	950	40

Table 2 Paired comparison pilot rankings: formation task

Pilot	Ranking (best → worst)	k
1	*F2-NA-F1*	1.00
2	*F2-F1-NA*	1.00
3	*F2-NA-F1*	1.00
4	——	0.00
5	*NA-F2-F1*	1.00

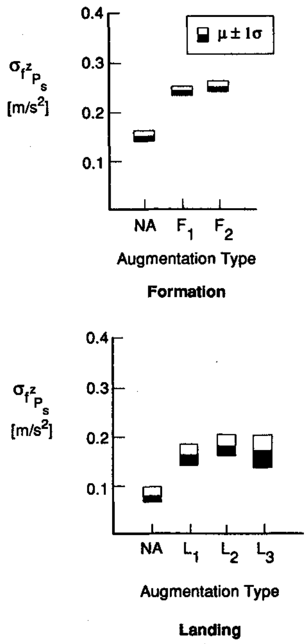

Fig. 7 Simulator heave: standard deviation of specific force.

ployed in the present study. For this reason details of this aspect of the study are not included here. They can be found in Ref. 2.

Formation Flight

The responses to the three questions concerning the realism of the three cases *NA*, *F*1, and *F*2 are summarized in Fig. 8. The pilots' responses to the first question indicate that all three cases were felt to add to the realism of the simulation. This overall acceptance of *F*1 and *F*2 indicates that the proposed method for augmenting turbulence-induced motion does not detract from the realism of the simulation. The responses to the second question were less encouraging. In the case of the third question it appears that all cases compare favorably with other training simulators.

The paired comparison results of Table 2 indicate that *F*2 was preferred over *F*1. Also shown in Table 2 is the within-judge coefficient of consistency k. If a pilot's results are perfectly consistent, then k will be 1.0. If, on the other hand, his judgements exhibit the maximum inconsistency, then k will be 0. In Fig. 9 the analysis of the paired comparison data following the procedures outlined in Ref. 5 ranks the three cases along a linear scale from worst to best. The order has *F*2 ranked as best and *F*1 as worst. In this instance the in-

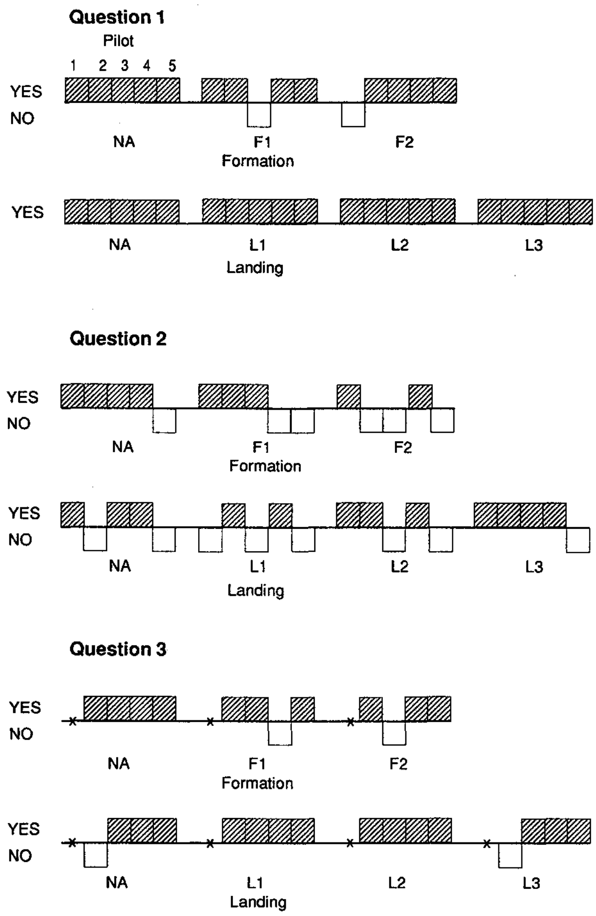

Fig. 8 Questionnaire responses.

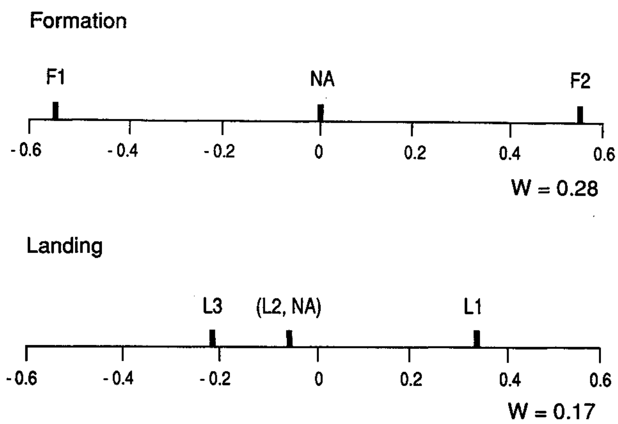

Fig. 9 Paired comparison ranking.

terjudge consistency is indicated by the coefficient of concordance W. The value of W will lie between 0 and 1, with 1 representing complete interjudge consistency. Here, W is 0.28, and this is similar to levels found in other simulator studies.[4]

Landing Approach

The responses to the three questions concerning realism are contained in Fig. 8. The pilots' responses to the first question were a solid yes for all cases. They unanimously felt that all four cases added to the realism of the simulation. As with the formation flight, for the second question, except for the *L*3 case, approximately half the pilot responses indicated that the induced heave motion was comparable to that experienced in heavy transport aircraft. The responses to the third question indicate that all cases compare favorably with other training simulators with only one pilot disagreeing in the cases of *NA* and *L*3.

Table 3 Paired comparison pilot rankings: landing task

Pilot	Ranking (best → worst)	k
1	$L2$-$L1$-NA-$L3$	1.00
2	$L1$-$L2$-$L3$-NA	1.00
3	——	0.20
4	——	0.20
5	NA-$L3$-$L1$-$L2$	1.00

The paired comparison results are shown in Table 3 and Fig. 9. It can be seen from Table 3 that two of the pilots produced inconsistent results, both with $k = 0.2$. The ranking from Fig. 9 in decreasing order of preference is $L1$, ($L2$, NA), $L3$. However, with a coefficient of concordance of $W = 0.17$, it would appear that the order of preference is highly dependent upon which pilot you interrogate. This is reflected by the close grouping of the ranking numerical values on the linear scale when compared with the wider separation found for the formation flight results.

Summary

The turbulence-induced motion augmentation technique proposed in Ref. 1 has been tested by a group of five evaluation pilots flying the UTIAS flight research simulator configured as a B-747. Two distinct flight regimes were employed: 1) a high-altitude task and 2) a low-altitude landing approach. In each instance several augmentation versions were evaluated.

The results of the study indicate that it is possible to augment turbulence-induced simulator motion and achieve a significant increase in the heave specific force levels without exceeding the travel limits of the motion system when a pilot is in the loop. In the present instance this was accomplished even though the process started with a turbulence-induced motion case judged to be already realistic. It was found that the augmentation process produced turbulence-induced motion judged to be realistic and to compare favorably to other training simulators.

The paired comparison tests ranked the various transfer function cases from best to worst based on how well they represented the simulated aircraft's response to turbulence. For high-altitude formation flight the order was $F2$, NA, $F1$, and for a low-altitude landing approach the order was $L1$, ($L2$, NA), $L3$. Thus, in both instances second-order transfer functions were judged to be best. Surprisingly, NA was judged to be superior to $F1$ and $L3$.

Only NA for the formation flight and $L3$ for the landing approach were judged to compare favorably with turbulence response in heavy transport aircraft. This may reflect on the overall simulation environment, the tasks performed, and the difficulty of relating the present simulator motion to past infrequent experiences in actual aircraft.

On balance it appears that if a simulator is given poor ratings due to insufficient turbulence-induced motion then the proposed motion augmentation technique could be successfully used to correct the problem.

Acknowledgments

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