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Off-Line Comparison of Classical and Robust Flight Simulator Motion Control

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This paper presents a comparison of the motion produced by a flight simulator using conventional washout filters and a novel robust controller. Both approaches are implemented in an off-line MATLAB™/Simulink simulation that includes a model of an electrically driven synergistic motion-base flight simulator. To evaluate the performance of these motion-base control approaches, the authors simulated the Boeing 747 airliner using a nonlinear model of its dynamics. The motion experienced by the aircraft pilot is compared to that experienced by the simulator pilot, using both control approaches. Additionally, the model used for the simulator motion base is adjusted to represent two different scenarios: a high- and a low-fidelity motion system. It is shown that the two control approaches reasonably track the motion of the aircraft, within the limitations of the motion base, but that the robust controller is able to compensate for variations in the fidelity of the motion system.

Introduction

MODERN flight simulators are composed of a number of subsystems that combine to provide the pilot with an environment that approximates that found in the real aircraft. One of these subsystems is the motion base that moves the simulator cockpit to provide realistic motion cues to the pilot. It is widely acknowledged that a good, properly controlled motion base can significantly enhance the overall quality of simulation realism. It is also widely acknowledged that a poorly controlled motion base, which results in erroneous motion cues, can be more detrimental than no motion at all.

In most commercial flight simulators, motion is achieved via a two-step process, represented schematically in Fig. 1; the aircraft motion is processed by a washout filter (WO) to produce a desired simulator motion. This simulator motion, usually in the form of actuator lengths, is used as commands to the motion base. A hardware- or software-based low-level controller (LLC) then ensures that the commanded motion is tracked as accurately as possible. The feedback loop of the LLC, which is typically based on measured actuator lengths but which could also include rate feedback, allows the LLC to issue commands to the motion-base actuators that compensate for tracking errors. In this conventional scenario, there is no feedback from the actual motion of the simulator to the washout filter, and therefore the washout filter and the motion commands it produces remain independent of any errors in the motion. Modern hydraulically powered flight simulators are usually equipped with a good LLC. Thus the designer of the washout filter software can usually assume that the simulator has perfect dynamics, i.e., that it will faithfully produce the motion that the washout filter commands.

However, a consideration of simulators with poor dynamic response is becoming increasingly important because the burgeoning interest in low-cost motion bases, particularly electrically driven ones with limited bandwidth and power. In such systems, it may not be wise to presume that the commands from the washout filter to the simulator motion base are accurately reproduced. It may then be important for the designer of the washout filter software to incorporate a knowledge of the motion-base dynamics into the design of the motion-base drive algorithms.

In the conventional two-step scenario of controlling a flight simulator motion base, the second step (the LLC) has typically been neglected in the literature, whereas attention has been focused on methodologies for designing washout filters. Many methods have been proposed to accomplish this task, including classical,[1,2] linear optimal,[3,4] and adaptive washouts,[5,6] and some of these have been evaluated in Ref. 7. In these works, the effects of the motion-base dynamics on the washout design were ignored.

Recently, robust control techniques have been applied to this problem, with emphasis on the case where the simulator dynamics are poor, e.g., limited bandwidth, low-drive power, or simple/inaccurate simulator position control.[8] Unlike the standard washout filters, the proposed methodology leads to a closed-loop controller, with feedbacks of the simulator position, attitude, angular rates, and if available, accelerometer measurements. Simulator dynamics can be improved by these feedback loops. The key difference of this type of control approach compared to the classical methodologies is that it addresses the issues of motion-cue generation and motion-base control as a unified problem. In addition, the approach is model based and the design incorporates a dynamics model of the motion base, of the human vestibular system, and of the simulated aircraft. As such, the robust controller will potentially compensate for poor motion-base dynamics, and will emphasize motion-cue generation to frequency ranges dictated by the simulated aircraft dynamics while accounting for the dynamic characteristics of the human pilot motion sensory system.

This paper presents a study of the motion produced by the earlier mentioned conventional and robust control approaches. Both approaches are implemented in an off-line MATLAB™/Simulink simulation that includes a dynamic model of the electrically driven synergistic motion-base research flight simulator of the Philadelphia Control Laboratory at the Technion (shown in Fig. 2). The comparison is based on a numerical simulation of a Boeing 747 airliner, incorporating nonlinear aerodynamics and engine models in a variety of maneuvers. Our main goals were to 1) demonstrate the functioning of a robust global controller design that treats motion-cue generation and motion-base control as a single problem, 2) show that for high-fidelity motion systems this approach can produce similar motion characteristics compared to the acceptable classical solutions, and 3) demonstrate that the robust control approach can effectively compensate for changes or uncertainties in the motion-base dynamics.

Simulator Model

Modern flight simulators typically consist of a mechanical hexapod arrangement of six linear actuators, also known as a Stewart Platform. Most often, the actuators are hydraulically driven, but in the present work, we consider an electrically driven system that

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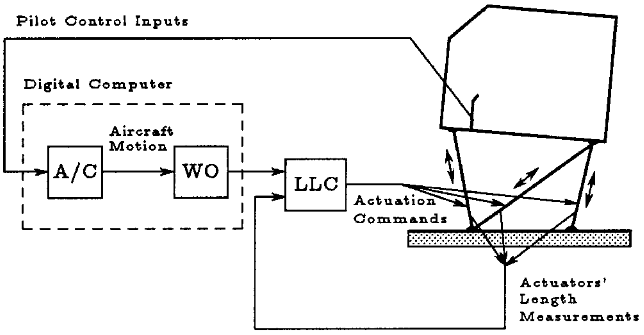

Fig. 1 Conventional two-step approach to generation of motion.

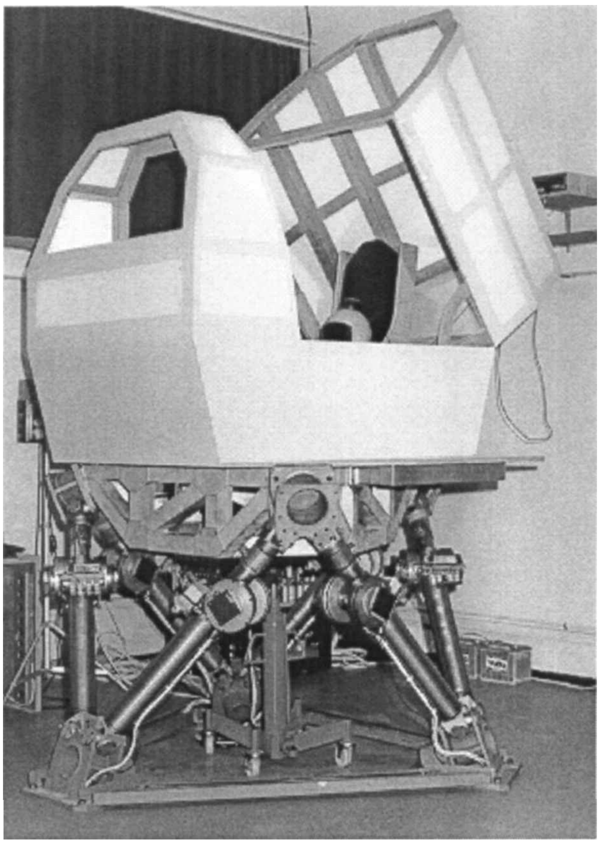

Fig. 2 Technion research flight simulator.

has poorer dynamic characteristics. The Technion research flight simulator, shown in Fig. 2, include two components in its LLC: an analog hardware-based feedback loop and controller, as well as a software component that further enhances the performance of the motion base. The nonlinear model of the motion base used in this study, including only the analog feedback loop, was previously validated experimentally as reported in Ref. 8.

With only its analog feedback loop, the simulator has poor motion characteristics and thus requires additional control to be used in conjunction with a conventional washout filter. We therefore augmented the analog controller using an additional feedback, which is implemented in software. The main function of this additional feedback is to incorporate integral control into the LLC. As a whole, the combined hardware and software controllers can be lumped together and modeled simply as six PID (proportional-integral-derivative) controllers. Because the model of the motion base can incorporate any PID gains, it is apparent that the simulation affords the flexibility to represent a variety of dynamic characteristics of the simulator with its LLC.

In the present work, one of our objectives was to study the effects of varying motion-base dynamics characteristics on the resulting simulator motions and pilot-sensed motion cues. To do this, we

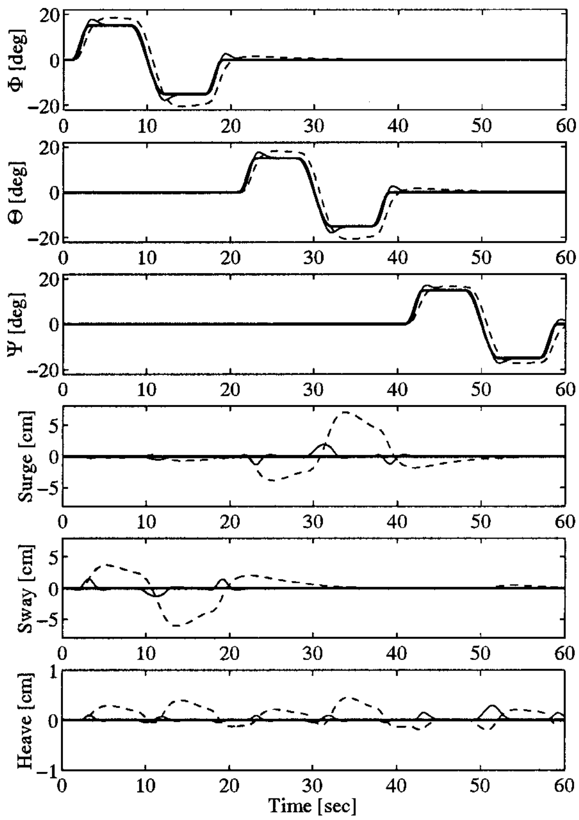

Fig. 3 Simulator dynamic response: ——, command; ——, high; and – – –, low gain actuator controllers.

tested two simulator configurations. These differ in their feedback gains in the low-level position control loop. The two sets of gains are used to represent a high-fidelity (stiff) and a low-fidelity (loose) simulator motion base. The first set consisted of higher gains, leading to relatively high bandwidth, short settling time, and moderately dampened closed-loop system. The second control system incorporated lower loop gains, resulting in a lower bandwidth and slower system. The two sets of gains were chosen to represent extreme cases used for evaluation and comparison purposes.

A comparison of these two controlled motion bases for 15-deg roll, pitch, and yaw doublet commands is shown in Fig. 3, clearly demonstrating the different dynamic characteristics of the resulting controlled systems. The high gain system exhibits quick response with moderate overshoot and relatively small cross-coupling. An inferior response is shown for the lower gain system, which, although better dampened, demonstrated slow convergence and strong cross-coupling. In both cases, the cross-coupling effect is significant during the transient response. Similar results were obtained for commands in the translational degrees of freedom.

The simulator model described earlier, which was validated experimentally in Ref. 8, was linearized and used in the robust controller design as described in the following sections. As such, this design methodology is model-based, whereas the classical washout approach makes no explicit use of a simulator model. This therefore comprises one of the key differences between the two approaches.

Motion-Base Control

The motion base, with its associated feedback loops already described, would typically be delivered in hardware by the simulator manufacturer. At this stage, an additional software component is required to transform aircraft motions into simulator motions for reliable motion-cue generation. In conventional simulators, this is typically accomplished using a washout filter, and in the present work a classical washout[7] will be used as representative of the first step in the conventional two-step approach to flight simulator control. Its performance will then be compared to a robust motion-cue controller.[8] This section briefly describes these two motion control techniques.

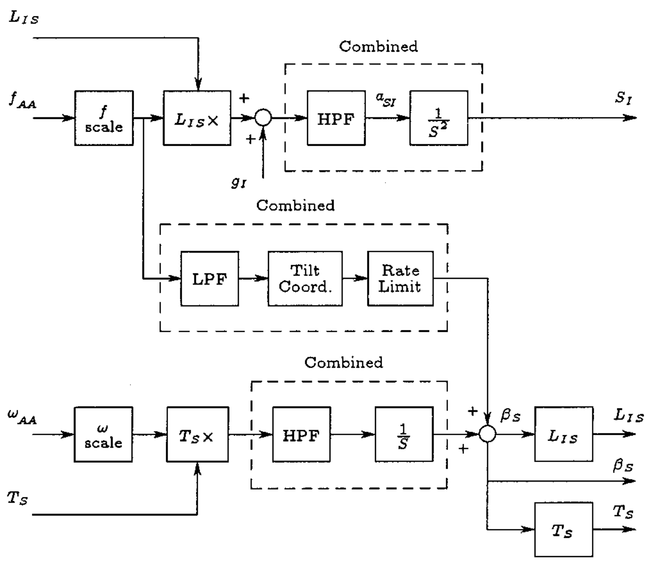

Fig. 4 Layout of the classical washout filter (reproduced from Ref. 7).

Classical Washout Filter

The function of a washout filter is to accept aircraft motions as inputs and, from it, to produce desired simulator motions so that the simulator pilot motion sensations are as close as possible to those experienced in actual flight, although remaining within the limited confines of the allowable motion-base travel. This is a difficult task, fraught with compromise. A variety of methods have been proposed to accomplish this task.[1–6] The most widely accepted of these is the classical washout. Using a previous study of washout filters[7,9] as a guide, we adopted the classical washout filter layout shown in Fig. 4. This filter accepts the three components of aircraft specific forces and three components of angular rates as input and generates the desired simulator displacements.

This layout consists of three channels (though each channel is also multidimensional): a translational high-pass, a rotational high-pass, and a translational-rotational low-pass cross-feed (typically known as tilt coordination). These are now described in more detail.

1) The topmost channel operates on the aircraft specific forces (at the cockpit centroid), expressed as components in the body frame. These are first passed through a scaling/limiting block. In the present work, the scale factor was set to unity on all channels, and the limiting levels set high enough that they were never reached. The resulting signals are transformed into the inertial frame and the gravitational component is removed. The resulting accelerations are then high-pass filtered and integrated twice to obtain a commanded simulator centroid position. In the coefficient set we used, denoted as CW2 (classical washout 2) in Ref. 7, these filters were linear and of second order.

2) The bottommost channel operates on the aircraft angular rates, expressed as components in the body frame. Again, these are passed through scaling and limiting blocks with characteristics chosen such that they make no alteration of the signals (see preceding item). The angular rates are transformed into Euler angle derivatives. These are then filtered and integrated once to obtain the high-frequency component of the simulator Euler angles. In the CW2 (Ref. 7) coefficient set, these filters are linear and of first order.

3) The middle channel operates on the scaled and limited x- and y-specific forces. These are low-pass filtered through linear second-order filters and converted into equivalent tilt angles. These angles are then added to the high-frequency component of the Euler angles to obtain the commanded simulator Euler angles. It should be noted that this crossfeed channel includes a rate-limiting element that keeps the tilt rates below 3 deg/s.

In essence, the preceding filters work by removing all direct translational and rotational low-frequency components and attempting to produce only the high-frequency components directly. Because the low-frequency components are those that would tend to drive the simulator past its limits, the filters effectively limit the commanded motion of the simulator motion base. The only low-frequency components that are reproduced are those contained in the x- and y-translational motions, which are produced by tilting the cockpit. On the presumption that these are moderate in magnitude, the associated tilt angles tend also to be moderate and therefore within the capabilities of the motion base.

A key element in the design of the washout filter is the choice of the break frequencies and damping ratios of the various high- and low-pass filters. These will dictate what frequencies are attempted and the overall magnitude of motions that will be commanded to the motion base. In the present work, we have not modified this facet of the CW2 coefficient set given in Ref. 7, and therefore we expect that the motions produced by our classical washout filter would be found acceptable by airline pilots.[9]

One of the key advantages of the classical washout filter is the ease with which its motion characteristics can be adjusted.[7] For any alternative motion control methodology to be considered practical, it should not seriously increase the complexity of the motion tuning task because motion is sometimes adjusted in the field to satisfy particular airline acceptance pilots.

However, one problem of motion control that the classical washout does not address is introduced by a low-fidelity motion base. That is, it makes no attempt to correct its motion commands in cases where it is known, a priori, that the motion base is unlikely to follow those commands. Much of the reason for this omission is that washout filters have most often been developed for hydraulically powered motion bases that tend to have excellent motion fidelity.

Robust Motion-Base Control

The robust motion-base control methodology evaluated in this paper allows the design of a closed-loop controller for motion-cue simulation with a feedback on the measurements of the actual simulator motion. Using this approach, the conventional two-stage motion control can be replaced by a single controller and can potentially eliminate the low-level actuator length control. If the low-level control is kept for maintenance and simple position control, the closed-loop controller provides motion-cue simulation that compensates for the dynamic characteristics and inaccuracies of the low-level controller.

Similar to other motion-cue controllers, the goal of the closed-loop controller is to provide the pilot with realistic wideband motion cues, resembling the actual flight sensations. The controller design is based on a linearized model of the simulator dynamics, including its uncertainties and motion constraints. In addition the design accounts for the dynamic characteristics of the motion sensory system of the pilot, mainly the vestibular system, and incorporates the simulated aircraft dynamics model to quantify the motion-cue excitation. This way motion-cue simulation and control requirements are tuned to the relevant frequency range only, determined by these models.

The controller design setup, which includes the preceding models and various performance specification weighting functions, is presented in Fig. 5. The central part of this setup is the simulator dynamics model. In the current study, the simulator's low-level position controller is incorporated as part of the simulator model.

The design goal is to compute a closed-loop linear dynamic controller $\boldsymbol{K}$, the inputs to which are simulator sensor readings and motion-cue commands generated by the simulated aircraft model, the A/C block in Fig. 5. The controller outputs are the commands $\underline{u}$ to the simulator actuation system. In the current design, the measured inputs to the controller include simulator position, attitude, and angular rates, a total of nine measurements. The noisy sensor readings are modeled by the white random input $\underline{n}$ and its shaping filter W_n. Realistic limits on the actuation system commands are introduced by the W_u block.

In actual simulations, the aircraft model is excited by the pilot controls $\underline{\delta}$, such as the stick, pedals, and throttle. In the design process, the A/C block can incorporate either a linearized model of the (usually) nonlinear model of the aircraft, or an approximate transfer matrix that expresses the frequency content of the various motion cues to be reproduced by the motion-cue controller. The pilot excitation characteristics, e.g., magnitude and bandwidth, can be also incorporated in this A/C block.

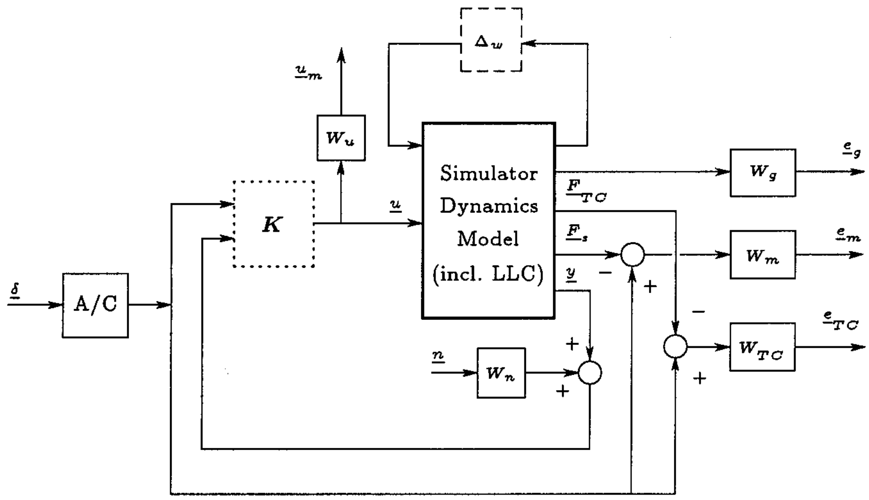

Fig. 5 Robust motion controller synthesis interconnection model.

Uncertainties in the simulator dynamics model, incorporated in the Δ_w block of Fig. 5, can account for the model linearization errors, as well as actual uncertainties in the simulator mass/inertial properties and errors in the model of the actuator drive system (electrical or hydraulic). The controller is designed to perform adequately for a specified range of variations and changes in these parameters. Consequently, no controller redesign will be required as long as simulator changes, such as alteration in its inertial properties because of additional equipment installed on the simulator or variations in the actuator drive characteristics because of degradation in the electrical or hydraulic supply system, are within the design limits.

The motion-cue accuracy requirements are represented in the interconnection model by the weights W_m and W_{TC}. Compared to the classical washout, W_m is similar to the high-frequency motion-cue simulation channels. The input to this block is the difference between the aircraft motion cues and the sensed specific forces and angular rates at the simulator pilot head location $\underline{F}_s$. In this channel, only high-frequency components of this difference are required to be small. The frequency shape of W_m can be constructed based on models of the human motion sensory system, as was discussed in Ref. 8. Similar to the classical washout, the low-frequency motion-cue simulation is obtained by tilt coordination, represented here by the W_{TC} block. The input to this block is the difference between the commanded specific forces and the specific forces due to gravity and the simulator tilt $\underline{F}_{TC}$. The W_{TC} imposes only low-frequency requirements for specific force simulation using simulator tilt, i.e., roll and pitch. Overall, W_m and W_{TC} are the main design parameters, and their tuning is, to a large extent, similar to the tuning of the classical washout filter parameters.

Finally, simulator motion limits are specified using the block W_g. These include limits on the simulator translations and rotations, and in particular, the requirement for the simulator to return to its neutral position between the aircraft maneuvers. Additionally, angular rate limits on tilt coordination are also introduced in this block.

In the robust control context, a controller $\boldsymbol{K}$ that will ensure a closed-loop transfer matrix gain of less than one between the appropriately scaled model inputs ($\underline{\delta}$, $\underline{n}$) and outputs ($\underline{e}_g$, $\underline{e}_m$, $\underline{e}_{TC}$, $\underline{u}_m$) will provide the required motion-cue simulation performance in the presence of the simulator dynamics uncertainties. In this work, because of the structural model uncertainty, the μ synthesis and analysis technique[10,11] was applied to compute the linear dynamic controller $\boldsymbol{K}$. The two different simulator dynamic models, governed by the two LLCs used (stiff and loose,) lead to two different controllers $\boldsymbol{K}$. It is interesting to point out that the two controllers were synthesized using the same design parameters, i.e., weighting functions. The relatively high order of the controller was reduced from 54 to 38, with only a minor effect on its performance. Initial real-time evaluations suggest that these controllers can be easily implemented on current personal computers at a sampling rate of at least 200 Hz.

Discussion

Among the key differences between the conventional and robust control approaches are that, in the design process, the latter explicitly includes a (linearized) aircraft model, or in the broader sense, a knowledge of the frequency content of the aircraft motion cues, a consideration of simulator motion limits, and a model of the vestibular system, which can be interpreted as frequency-dependent function of motion-cue accuracy requirements. As such, the robust control approach can be said to be more systematic in its filter design.

However, it can be argued that considerations of frequency content and motion limits are implicitly present during the design of conventional washout filters because the filter coefficients are tuned[7] to accommodate both the natural motion of the aircraft as well as the sensations of the evaluation pilots. Both approaches must, in the end, be tuned by trial and error to the satisfaction of evaluation pilots to ensure that they will produce realistic motion cues. In the case of the classical washout, this is done by direct manipulation of the filter coefficients, whereas in the case of the robust controller, this is done by manipulating the weights at the design stage. It is well known that tuning of the classical washout is relatively straightforward[7] and that this is one of the key benefits of this approach. Based on our experience with the robust controller, tuning it is also a reasonably transparent process: A desired change in the motion characteristics is obtained by modifying the appropriate weighting functions (see the description of W_m and W_{TC} presented in the preceding section). However, because of relatively shorter experience with the robust controller in a realistic tuning scenario with pilots, this aspect of the controller remains to be investigated in further detail.

Another key difference between the two approaches is that the robust controller incorporates into its design a knowledge of the simulator's dynamic characteristics and therefore is able to compensate for motion inaccuracies. In addition, certain variations in the parameters of the simulator, such as inertial and actuation properties, can be accommodated without a redesign of the controller, as long as they are within the limits included in the design process. By contrast, the classical washout incorporates no mechanism to accommodate a knowledge of the simulator's characteristics. The only avenue that could be pursued to compensate for this in the context of the conventional two-step approach would be a redesign of the LLC using a model-based robust control technique. Though this approach is certainly worthy of consideration, we chose to focus on a comparison between a strictly conventional approach (classical washout with conventional LLC) and a global approach in which motion-cue generation and motion-base controller design are treated concurrently. We expect that this latter approach will yield the most potential benefits because it will not attempt to reproduce motions outside of the range that a human pilot would sense. By contrast, any two-step approach would blind the motion-base controller design to the characteristics of human motion sensation and might therefore be needlessly stringent.

Finally, it should be noted that although the classical washout cannot compensate for a poor LLC, it also places no requirement on the designer to obtain an explicit model of the flight simulator motion base and its LLC, thereby making the design process substantially simpler. Thus, the fact that the classical washout is not model based entrains both advantages and disadvantages. The relative balance of these will depend mainly on the particular application considered and the fidelity of the motion base being used.

Comparison Methodology

To compare the earlier mentioned methods for generating flight simulator motion, we used both the classical washout and the robust control approach to generate the motion in three typical maneuvers of a simulated Boeing 747 airliner. A MATLAB/Simulink simulation of the complete software/hardware system was used to generate the simulator motions that would be expected for different combinations of LLC and motion-generation methodology.

Outline

Figure 6 shows the general system layout used for the four different test cases that were evaluated. The position of switches S_L and S_M represent the different LLCs and motion-generation schemes, respectively. The stiff and loose low-level controllers are represented by LLCS and LLCL, respectively, and RC(S_L) is the robust controller. Clearly, the latter is a function of the LLC used: We have two robust controllers, one for LLCS and one for LLCL. Thus, with S_L in its lower position and S_M in its upper position, we would be using the classical washout with the LLCL. Each of the four possible configurations was tested with each of the three aircraft maneuvers described next, for a total of 12 test cases.

Evaluation Maneuvers

Three characteristic maneuvers were used to perform the comparisons: a takeoff maneuver, a turn-entries maneuver, and a throttle-pulse maneuver. These were chosen to ensure that relatively few maneuvers would provide a broad range of sensations. A brief description of each maneuver follows.

Takeoff Maneuver (TOM)

This maneuver begins with the aircraft at a speed of 50 m/s on the runway, with the throttle lever at 15% of maximum power. At $t = 3$ s, the throttle is advanced to 100% power. The aircraft accelerates and at $t = 11$ s reaches its rotation speed. The nose is lifted and, soon after, the aircraft takes off at a pitch angle of 10 deg. At $t = 17$ s, the right outboard engine fails and the pilot eases the elevator to avoid stalling. The maneuver ends at $t = 25$ s.

Turn-Entry Maneuver (TEM)

In this case, the aircraft begins in a cruise condition at an altitude of 6280 m and a speed of 212 m/s. Soon after, the pilot initiates a roll to the right and maintains a steady roll angle. At $t = 12$ s, the pilot initiates a roll to the left to attain a left-wing down attitude. This whole sequence is then repeated a second time, until the maneuver ends at $t = 40$ s. The maximum bank angle reached in each roll is approximately 40 deg.

Throttle-Pulse Maneuver (TPM)

This maneuver starts at the same cruise condition as the TEM, with 55% power. At $t = 1.5$ s, the throttle is suddenly increased to maximum power, and the pilot attempts to keep the aircraft horizontal. Seventeen seconds later the throttle is set to idle until the end of the maneuver at $t = 40$ s.

Results and Discussion

The simulator motion cues are evaluated for different combinations of motion-base fidelity and control methodology. The specific forces at the pilot's head and the angular rates of the aircraft are compared to the corresponding quantities that would be experienced by the simulator pilot for each of the three maneuvers. In these comparisons, the four different hardware/software scenarios are labeled as follows: WS, the classical washout with LLCS; WL, the classical washout with LLCL; RS, the robust controller with LLCS; and RL, the robust controller with LLCL. In the sequel, a qualitative discussion of the relative performance of each approach is presented, based on a visual inspection of the results.

Takeoff Maneuver

The left-hand side of Fig. 7 compares the specific forces and angular rates that the pilot would experience in the TOM, as well as those that would be experienced by the simulator pilot for each combination of motion controller and LLC. The right-hand side of this figure also presents the simulator travel required by each of the four simulator arrangements. An inspection of these results shows that, in general, the simulator plots tend to resemble each other, so that we might expect a pilot to find them similar. In addition, Fig. 7 shows that the two approaches use similar amounts of motion-base travel, though there are significant differences in the shape of the curves, especially in the translational displacements. Another general observation is that the curves for the robust controller with the stiff and loose LLC are very close to each other, to the point of being indistinguishable for much of the maneuver. By contrast, the curves for the classical washout with stiff and loose LLC differ substantially from each other. This makes it apparent that the robust controller is effective at its intended task of compensating for different motion-base characteristics.

Further similarities are observed between the two types of motion control: 1) the yaw rate curves are similar in shape; 2) both approaches do a poor job of simulating vertical specific force, primarily because there is no known way of simulating sustained vertical accelerations in a synergistic motion base; and 3) both methods have a reverse cue in a_x and a_y at the onset of tilt coordination.

Upon closer inspection, a key difference becomes apparent between the classical washout and the robust controller. The tilt coordination tends to be faster for the robust controller, thereby enabling it to better track the a_x and a_y specific forces. The tilt rate limit of 3 deg/s of the classical washout prevents specific forces from

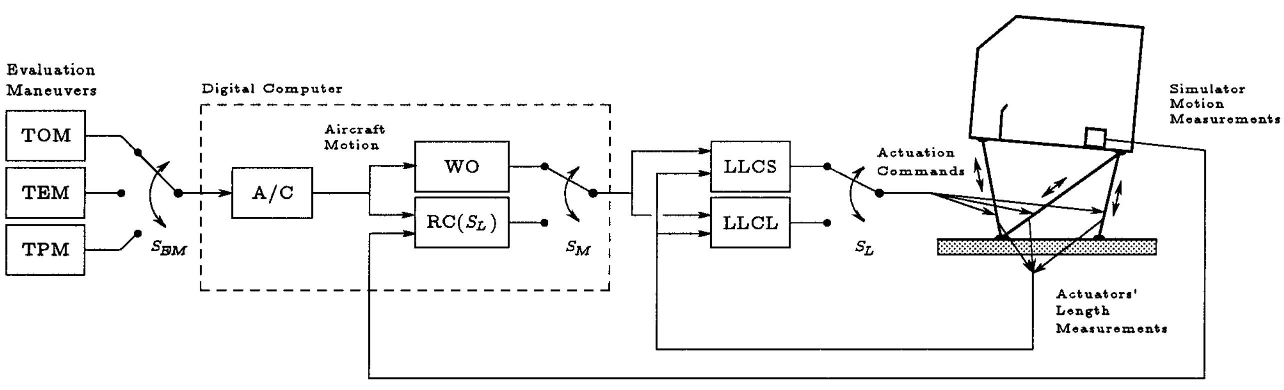

Fig. 6 Comparison methodology outline.

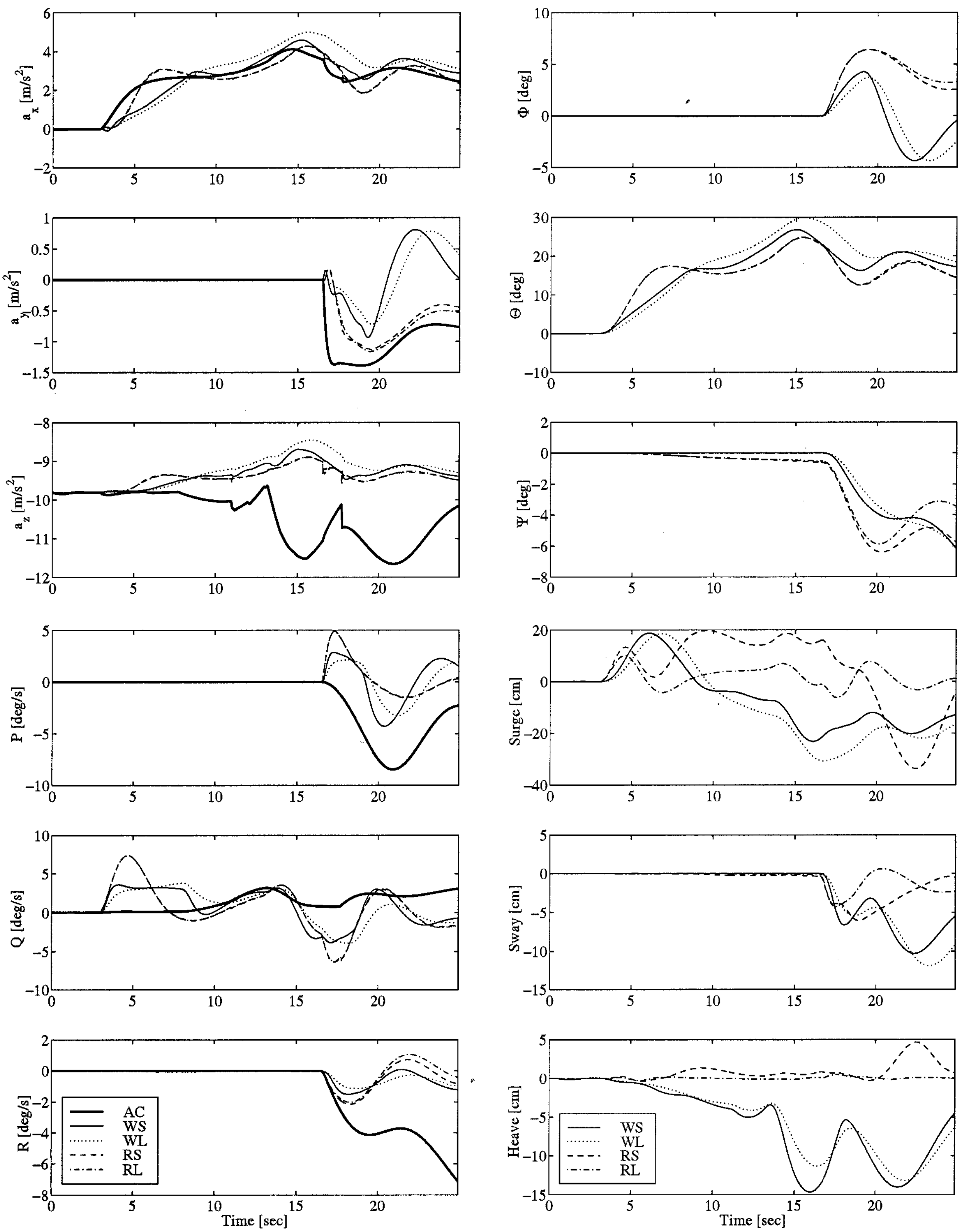

Fig. 7 TOM simulation results. Left column plots present aircraft and simulator specific forces and angular rates. Right column plots present the corresponding simulator motion.

building up as quickly as they might. The flip side of this is that the pitch and roll rates of the classical washout better track those of the aircraft. Whether the overall effect turns out to be more realistic for the robust controller or for the classical washout can only be determined by piloted evaluations.

Turn-Entry Maneuver

Figure 8 compares the specific forces, angular rates, and simulator travel for the TEM. Many of the observations in this maneuver parallel those in the TOM. Again, the general shape of the curves is quite similar for the two types of controllers, and again, the robust controller is much less affected by changes in the LLC. Here too, all controllers are poor at simulating the vertical specific force, primarily because there is no known way of simulating sustained vertical accelerations in a synergistic motion base.

The near-coordinated turns of this maneuver, typified by a large roll rate but small lateral specific force, are challenging for a flight simulator. Because the motion base is Earth fixed, any attempt to

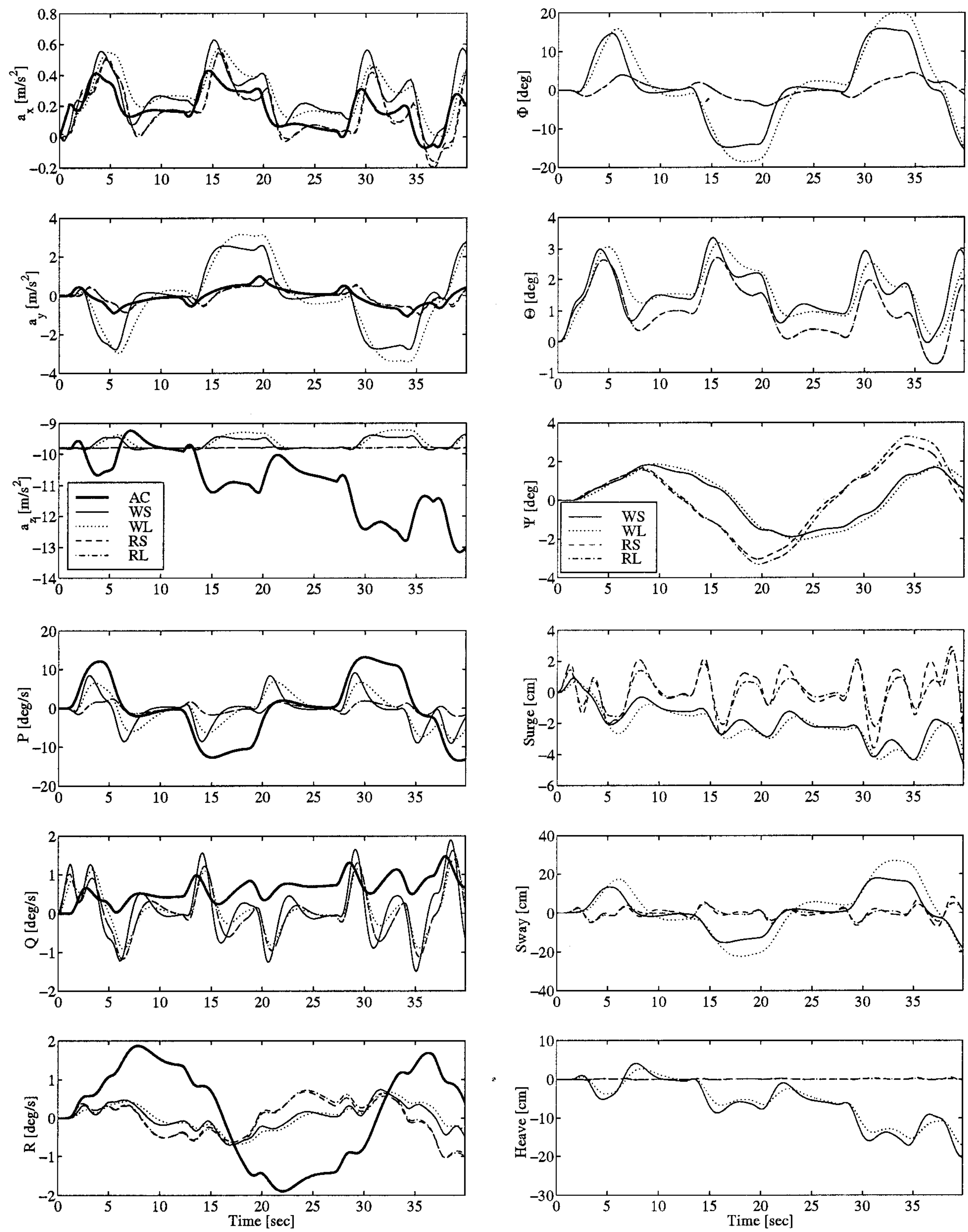

Fig. 8 TEM simulation results. Left column plots present aircraft and simulator specific forces and angular rates. Right column plots present the corresponding simulator motion.

produce a large roll rate will come at the penalty of a large lateral specific force. As such, the best compromise motion tends to be one in which a good roll onset cue is provided, but which is soon washed out to zero to avoid building up too much lateral specific force. The exact balance between these two competing priorities that will be considered optimal is difficult to determine a priori, and often differs from one pilot to another.

In this maneuver, the classical washout uses substantially more simulator travel because 1) the simulator tilts substantially in roll, 2) there is more lateral motion, and 3) there is a significant upward drift. Based on the plots, it is not clear that this additional motion is well used. The roll rate cue is a little better, giving more of the onset cue than the robust controller. By contrast, the lateral specific force is substantially worse for the classical washout. Again, how the balance of these would be perceived by the pilot can only be determined by piloted tests.

The general explanation for the differences in motion is that the rotational high-pass filters of the classical washout appear to be less

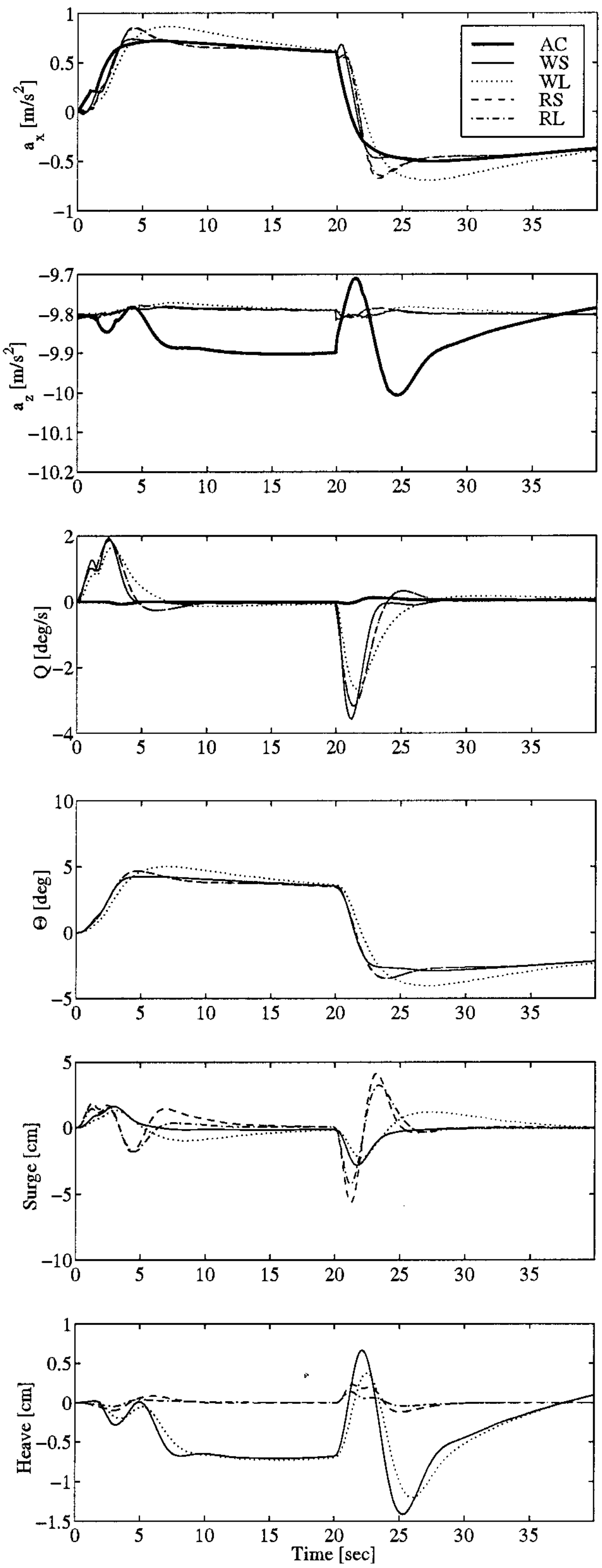

Fig. 9 TPM simulation results: longitudinal motion variables.

restrictive than the equivalent mechanism in the robust controller. As a result, more roll rate is admitted through the filter, and the cab rolls more. The roll rate cue is therefore better, but the ensuing roll angle then induces a lateral specific force that is detrimental, because the aircraft is undergoing what is essentially a coordinated turn, i.e., with zero lateral specific force. The robust controller does not yield nearly as much of this unwanted a_y because it tilts the cab much less, by a factor of about 5.

Throttle-Pulse Maneuver

Figure 9 shows only the longitudinal motion variables for the TPM. The lateral motion is omitted for the sake of economy of space, and because very little motion occurs in those variables as this is essentially a purely longitudinal maneuver. In this maneuver, the motion of all of the controllers is remarkably similar, primarily because this is a relatively gentle maneuver that can be simulated quite simply and well.

The classical washout appears to give a slightly stronger (false) reverse bump at the onset of tilt coordination than does the robust controller. Also, the classical controller with the loose LLC shows more evidence of lags than do the other cases. However, the results of this maneuver are more significant in highlighting how similar the motion produced by the two methodologies is than the differences between them.

Finally, it is noted that the classical washout used here was previously found to be acceptable by a range of evaluation pilots.[9] It is therefore expected that the robust controller motion presented here would also be perceived as acceptable and could form a good basis for further tuning.

Conclusions

Two different methodologies for flight simulator motion generation were evaluated for three different simulated maneuvers in high- and low-fidelity motion systems. It was found that the robust control approach considered could effectively compensate for inaccuracies in the motion-drive system.

The robust controller design is based on a model of the motion-base dynamics and control, whereas the classical washout is not model based. The robust controller is therefore more difficult to put in place. However, the added complexity does result in significant benefit because it can compensate for deficiencies in the motion-base dynamics characteristics.

The motion produced by the two approaches was significantly different, though a distinct preference for one or the other could not be ascertained without piloted evaluations. Both controllers were found easy to tune to achieve a desired behavior. Because the classical washout had already been tuned in accordance to pilot comments, the robust controller would have to be similarly adjusted prior to a piloted comparison of the two approaches. Future work will be aimed at implementing these motion controllers on the Technion flight simulator to allow piloted evaluations.

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