The Use of Full Flight Simulators for Accident Investigation

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Author Biography:
Robin Tydeman spent 20 years as a pilot in the RAF, primarily as a flying instructor on large aircraft. After attending the Empire Test Pilot School in 1985 he spent his final 3 years in the RAF evaluating large aircraft in the air-to-air refuelling role. He then flew as a commercial pilot on Boeing 737 aircraft before moving to Cranfield University where he instructed on Flight Test techniques. In 1994 he moved into flight simulation and was involved in the development of the first Boeing 777 simulators.

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Abstract

Flight simulation has become an indispensable tool for training within aviation. In little more than 50 years it has established a reputation for high levels of fidelity and the ability to provide an environment in which the effective training of aircrew can be conducted economically and safely. Flight simulation has also proven itself to be invaluable to the aircraft accident investigator. However, with the onset of digitally controlled simulators and compelling visual systems it is easy to become beguiled by the supposed 'fidelity'. Any dependency on simulation will invite legitimate questions about the validity of any subsequent conclusions, and may cast doubts on the technical veracity of the investigation as a whole. This paper suggests that the use of flight simulation in accident investigation should be approached with care, acknowledging the fact that simulators have limitations.

The traditional use of flight simulators in accident investigation is to use the digital data from the flight data recorder (FDR) to programme the simulator, usually a fixed base engineering simulator, which will then replicate the flight of the aircraft. Data from the air traffic control radar, TCAS units and the cockpit voice recorder can also be incorporated. Then, surely, the investigator has the complete picture! But how accurately does the simulator represent the aircraft and the ground and air environment in which it operates? Whilst many flight simulators have a debrief facility which allows simulator data to be replayed for training purposes a full flight simulator was simply not designed to accept data from the FDR; errors, particularly with systems integration, will occur. A malfunction of an aircraft system is often the precursor to an accident investigation; but how accurately are these malfunctions presented in the flight simulator? Furthermore, since pilots involved in accidents usually exhibit the symptoms of a high workload how can the simulator affect our understanding of the workload experienced by the pilot dealing with a problem?

In order to answer these questions I will start by considering the development of full flight simulators in order to identify those areas where the simulation can be expected to represent accurately the aircraft in flight and on the ground. The regulatory framework within which flight simulators operate will be outlined and will include the problems of data acquisition for malfunctions. The basic concepts of simulator modelling and its limitations will then be explained. Throughout the paper examples will be given of the potential for the miss-use of flight simulators in accident investigation.

The Development of Full Flight Simulators

In 1928, Edwin C. Link left his father's organ building business to begin work on a "pilot trainer." He envisioned a device that would allow pilots to take their preliminary flight instruction whilst remaining safely on the ground. With his background in organ building, he utilised air pump valves and bellows to make his trainer move in response to its controls. Introduced in 1934 it was later used for instrument flight training for virtually all North

American pilots during World War II, and was still in widespread use in the mid 60s. With a rudimentary motion system and no visuals it certainly had no pretensions to replicate any known aircraft; its sole purpose was to allow the pilot to learn to fly, and then practice, instrument procedures.

In the early 50's, with the advent of more complicated aircraft, the actual cockpit itself was used as a simulator. Taken from the production line and placed in the training centre it was clearly an accurate representation of the cockpit. The aerodynamic model was rudimentary, driving little more than the flight instruments in response to flight control inputs and there was no motion or visual system; however, it provided valuable training and laid the foundations for further simulator developments. At this stage the training conducted in the simulator also expanded to include normal and emergency procedures.

<u>Motion System</u> In an attempt to increase the realism of simulator training motion was introduced. There has subsequently been a great deal of debate within the flight simulator industry on the need for motion and many accident investigations have utilised engineering simulators which invariably have no motion systems. Is motion necessary in either case? To attempt to answer this question the RAND Corporation conducted a study in 1986 which evaluated US pilots flying the C17 flight simulator and showed that their performance was greatly enhanced through the use of a motion system. This should not be surprising; in the real world acceleration precedes displacement and, since our motion sensors detect acceleration very quickly cues of motion precede visual displacement. Research has indicated that the brain senses acceleration first (sec/100) whereas visual displacement cues follow (sec/10). When flying an aircraft the pilot has three main input sources of information:

a. The eyes; these provide his main input. The information from the instruments tells him his attitude, position in a space and, to a lesser extent, the rate of change of these variables.

b. The limbs, which tell him the position of the aircraft controls together with the force that he is exerting on them.

c. The vestibular system, which tells him when he is subjected to acceleration and, importantly, also stabilises his eyes.

Let us now consider the pilot in a flight simulator equipped with good quality, low latency motion platform and consider a sudden disturbance in flight. The pilot's vestibular system immediately alerts him to the disturbance, because it responds rapidly to the acceleration cues, and although this information may not tell him the exact nature of the disturbance, he is warned to monitor the instruments to detect a change. Since the instruments generally indicate the attitude or position of the simulator, the second integral of acceleration, there will be a delay following the acceleration before the instruments show the result of the disturbance. However, the pilot will now be primed to notice this change in indication as soon as it is discernible and can apply an immediate correction by means of the aircraft controls. This brings another feedback loop into operation which tells the pilot how much he has moved the controls together with the force resisting the movement. The acceleration generated by these controls is again sensed by the pilot's vestibular system and he is aware that the correction is taking effect even though the instrument may still be indicating the results from the initial disturbance. The pilot is thus able to predict what is going to happen to the simulator by means of these feedback loops and thereby utilise identical strategies to those used in the aircraft. It should therefore be clear that any meaningful assessment of pilot behaviour in an investigation should *only* be conducted on a simulator with a high fidelity motion system. The civil regulations have recognised the importance of motion and only a device with a motion platform is called a full flight simulator. Current regulations require a maximum time of 150 milli-seconds from the initial input to the last effect (normally visual) but this maximum time may well reduce in the future to reflect the increasing capability of motion systems.

Modern motion platforms are usually driven by six hydraulic actuators; by sending appropriate commands to all six actuators simultaneously motion in any of the aircraft six degrees of freedom can be obtained. But even the best motion systems have their limitations. This is not surprising when we consider that we are asking these six actuators, each about 5 feet in length, to provide all of the typical motion and vibrations cues experienced throughout the flight envelope of the aircraft, but whilst remaining firmly anchored to the ground. It has not been possible, so far, to generate prolonged 'g' and thus prolonged feedback cues to crew; this means, for instance, that during a tightening turn onto a final approach there will be no increase in stick force, an important cue to the pilot. Some simulators have attempted to introduce this cue but with varying degrees of success. Rejected takeoffs are an obvious area where there is simply not enough motion available to generate the correct cues. However, perhaps one of the most significant problems is that motion is not an exact science and is still correctly regarded as a 'black art'. There are always compromises to be made. One operator may decide that he requires a strong motion cue to simulate heavy braking and is prepared to accept the subsequent false cue provided by the high level of washout, another operator may prefer weaker motion cues but with no false cues. The only way to prevent any false cues being generated is to tune the system down until you cannot really feel anything. In addition, special effects are often exaggerated in order to conceal the lack of motion. How is the accident investigator to make sense of this?

<u>Visual System</u> The next step towards increased realism was to incorporate a visual system. Early systems used a model board but computer generated displays soon became available. Initially these were only capable of providing night/dusk scenes through a monitor display system with a limited field of view. Modern systems provide night/dusk/daylight scenes with realistic weather simulations and a horizontal field of view of 240° and 60° in the vertical. Of all the elements that comprise the modern flight simulator perhaps the most immediately impressive is the visual system. With the increased capability and availability of satellite imaging, together with the dramatic increase in economically priced computing power, the visual image is seductively authentic. Earlier visual scenes had a somewhat sterile appearance. Thus an airport would consist of a runway, with its attendant lighting, surrounded by grass and some stereotypical buildings. With little 'depth' in the scene and little to no textural feedback there were poor visual cues for the pilot during precise events such as the landing flare. Modern visual systems incorporate high levels of detail in areas such as the airport but the dilemma facing the visual modeller is that the volume of data representing this scene is almost infinite, yet the image generator will only accept a finite number of polygons (shapes) and textures. Texture is used like digital wallpaper and brings a life-like quality to otherwise sterile scenes without increasing the polygon count. It is typically used on flat surfaces such as grass, buildings etc but is also the technique used to display airport signs, people and vehicles. Importantly it is also used on runway surfaces and, whilst it may appear to be realistic from a distance, the texture surface produces an indefinite landing surface with little detail apparent during the final 30 feet prior to touchdown: once

again the pilot is deprived of realistic visual cues during the landing. There are other facets of current visual systems that do not assist the pilot during the flare manoeuvre such as restricted peripheral field of view on the older simulators, the importance of which, I suspect, is not really understood. Exactly what sensory inputs does the pilot process during the landing flare, and what is their relative importance. Until we honestly understand this process the simulator manufacturer does not know, with certainty, what he should provide in the simulation and the accident investigator is groping in the dark.

One of the practical problems associated with the visual database is keeping pace with the real world. For example I recently conducted training in all weather operations in a modern flight simulator. The airfield in use was Manchester, UK, which has had a second runway for 4 years, but this was still missing from our simulator visual database. It was decided that this did not affect the training needs, but would this be satisfactory in an accident investigation where the rapid assessment of the visual scene is an important element of the pilot's decision making process and thus workload?

<u>Conclusions</u> Having considered the development of the flight simulator it would be expected that modern examples would be able to replicate accurately the spatial layout of the cockpit. However, it may be pertinent to note that the cockpit is only simulated back to a defined line, usually around the back of the pilot's seat; the locked cockpit door, with its attendant distractions is not simulated. It would also be expected that the cockpit controls, together with their force feedback, accurately represented those in the aircraft, as did all displays. However, both the motion and the visual systems have their limitations. Most crucially the weakest area for these important sub-systems is that of integration, both with each other and the simulator as a whole. Any failure in integration will affect the performance of the pilot, albeit at a subconscious level. However, if an understanding of pilot behaviour is part of your quest, and it is difficult to accept that the investigator would not be seeking answers here, then you will have to be sure that all of the variables have been taken into account.

The Regulatory Framework

Flight simulators are used as a means to acquire, maintain and assess flight crew proficiency, and those operating within the civil sphere are designed to meet international regulatory requirements. The current definitive standard is a Level D simulator which allows for zero-flight-time training. The basic premise for the qualification of a full flight simulator was, and still is, that since the training and testing of aircrew would normally be conducted in a real aircraft any alternative to this must possess exactly the same characteristics and level of realism as the aircraft. Thus, once the regulator has evaluated the simulator to prove that it adequately represented the aircraft they will grant a **QUALIFICATION,** which implies a certain level of realism in comparison to the aircraft. Other factors are then involved in deciding the training tasks that may be carried out in the simulator, a process that is known as **APPROVAL**.

The simulator is constructed using 'Design Data' which originates from the aircraft manufacturer, supplemented by data from the vendors of any equipment fitted to that aircraft that can affect the realism of the simulation e.g. engines, autopilot, flight management systems etc. The simulator performance is then compared against the 'Check-out Data'. This data should have been collected from in-flight recordings on a particular aircraft of the type being simulated. Once the simulator demonstrates that it matches the 'Check-out Data', and when other objective and subjective tests have been completed, it receives its qualification.

<u>Malfunctions</u> Most malfunctions on modern aircraft types are part of, or supported by, the data pack and reflect correctly the procedures in the aircraft operating manual. Modelling component failures in these types invariable provides a correct simulation for the subsequent effects. The more reputable aircraft manufacturers now also provide simulation models that can be incorporated directly. Other malfunctions are the result of discussions between the simulator manufacturer and the operator who agree between them the cause and effect. But during the acceptance phase it is common for the operator's pilots, who are often senior training captains, to insist upon altering elements of the malfunction. One example that is repeatedly seen relates to engine failures after take off. Since this is one of the mandatory elements of training required during the pilot's routine simulator checks it is quite understandable that the acceptance pilots should wish to ensure its fidelity, and they will often demand more or less roll or yaw accompanied by higher or lower rates of motion. When I asked one senior training captain what he was using as his comparison he explained that he had suffered just such a failure in a Boeing 737-200; but he was accepting a Boeing 777! It is also common for acceptance pilots to base such judgements on the performance of other simulators that they have flown. However, as long as the acceptance pilot does not deviate too far from the baseline malfunction, whatever that is, who is to say that he is wrong? The simulator will be approved for training but is the engine failure that is modelled in the simulator the same as that which you are investigation? Engine failures in the simulator generally have muted responses in both motion and sound, but when reading reports of pilots suffering engine failures or surges in aircraft they will often use phrases such as 'It was like hitting a brick wall'.

Two issues fall from this. Firstly, if the pilot has been trained in a simulator that provides a different response to the aircraft during an engine failure, or any other malfunction, then has he been taught inappropriate behaviour? If so and he then makes a mistake in his initial reaction to the failure is it pilot error or a systemic error? Secondly, during the subsequent investigation, how does the investigator evaluate what cues the pilot used to identify the failure. I have suffered one engine failure and two engine surges in my career and in all instances it was a combination of the sound and motion cues that warned me of the malfunction. We have not even discussed the importance of sound to the pilot; for both normal and non-normal operations. It should be easy to obtain during routine operations even if we cannot capture the sound of an engine surge. But was that recording of normal operations completed with the flight deck door open? If that is the case the background sounds of air conditioning and engines are unrepresentative, as is the sound associated with the engine failure: or do we just pretend that sound is not important?

We have already accepted that modern flight simulators accurately represent the spatial orientation of the cockpit, but what happens with 'combo' simulators: i.e. those that represent more than one aircraft type. For example, there are many simulators that represent both the Boeing 757 and the 767 and pilots will often have a rating that covers both types. However, to reduce costs and to ensure that the 'down time' between simulator slots is kept to a minimum it is accepted practice that much of the overhead panel and control stand is left in place for both aircraft types, even though some of the controls are different. For example, on these aircraft types the hydraulic control panel, stabiliser trim indicator and stabiliser trim cut out switches are different, as are others systems to a lesser degree. Where is the fidelity here, and how can the accident investigator make valid judgements, unless he has carefully considered the consequences? Similar problems also occur with the Airbus A330 and A 340.

Within the simulator industry it has long been recognised that extraneous activity which can affect a pilot's workload is often not incorporated into the flight simulator. In an attempt to more accurately reflect the distractions encountered when flying into a busy airport modern flight simulators now have the capability to introduce extraneous air traffic transmissions and the more capable visual systems have much more traffic around, both on the ground and in the air. But there are other facets of simulation that more immediately affect the pilot. For example, ADF needles in simulators are invariably dead-beat whereas this is rarely seen in an aeroplane, and it has a real impact on the mental workload. Smoke, together with the need to fly with oxygen masks donned, create a very difficult cockpit environment and although smoke has been available on simulators for many years it is not frequently used. In the UK, for example, it is a requirement to inform the local fire brigade because prior to the use of smoke the fire alarms have to be disabled otherwise they will operate and may also initiate the sprinkler system!

Modelling and its Limitations

To further appreciate why I voice this note of caution it is necessary to understand what is involved in the process of simulation. Simulations are essentially dynamic processes that attempt to represent the behaviour of some aspect of the real world. Flight simulation sets out to represent the behaviour of a specific aircraft. However, in the flight simulator, apart from the physical representation of the cockpit interior, the aircraft simply does not exist. It is represented by a series of interrelated mathematical models that attempt to mimic the handling characteristics of the aircraft and its various systems. Moreover, the ground and the air environments in which it appears to perform are also only mathematical models. Thus the basis of the simulation is a family of models responding to each other in such a manner that their outputs, if channelled through a suitable device (the simulator) will give those in the cockpit the impression of being in control of an aircraft operating in the real world. Therefore, most modelling in the simulator, and particularly aerodynamic modelling, can only provide an estimate: once you move from the data point there is no longer any defined precision. It is accepted practice to interpolation between data points within the cleared flight envelope since this will probably not lead to erroneous responses; however how should the modelling be extrapolated outside of this flight envelope? This does become important when considering, for example, the use of flight simulators in upset recovery programmes with their attendant excursions in both pitch and side-slip. Thus, while the collection of models may give the illusion of an aircraft in flight they do not constitute an aircraft, even when flown aircraft data are used for the design and validation of the simulation. This produces limitations for the accident investigation that must be recognised.

The models on which a simulation is based are unlikely to fully represent the real world because of their range, complexity and variability: for instance, flutter is not modelled in any flight simulator that I am aware of. Moreover, some elements may be absent because of a lack of understanding of their influence or even of their existence. Even when the models are fully understood the designer of the simulation is often forced to simplify the representation of the real world in order to produce useable models. In addition, the operator or the manufacturer of the simulator may also restrict the level of detail contained in the simulation models. Knowing that modelling is an expensive process neither will want to include more complexity than is thought necessary to achieve the training objectives. This clearly has ramifications for the accident investigation where there are differences between the questions to be answered during the investigation and the training needs for which the simulator was designed.

Furthermore, the fidelity of the flight simulator is based upon the quality of the data package and whilst many of these are excellent some are not very good. In addition, the individual aircraft systems are developed separately from within this package and if they do not integrate seamlessly then the overall fidelity of the simulator will suffer. Moreover, system engineers, whilst excellent software engineers and very knowledgeable, may have had little or no experience of actually operating an operational system e.g. an aircraft braking system.

Implementing the Model

The full flight simulator is a ground based training aid and, despite the use of advanced computational techniques, sophisticated visual systems and cockpit motion systems employing acceleration-onset cueing it will have physical limitations to the extent to which it can represent the aircraft. It is important to remember that the simulator is successful because it does not conform to behaving like an aircraft. The aircraft cannot freeze its position in space, translate from one position to another in any direction, land without taking off, repeat a manoeuvre precisely and operate safely outside of its normal performance envelope.

In commercial aviation the aircraft that the simulator is attempting to represent is rarely stable as various fleet modifications are introduced. Sometimes these arise across the whole fleet and on others the variation may exist only on recently introduced versions of the aircraft. In an ideal world these changes would be immediately reflected in the simulator but if the simulator does not retain an absolute resemblance to the aircraft how valid are any of the conclusions made by the accident investigator. Some may argue that absolute compatibility with the aircraft is unnecessary if it only involves the positioning or standard of an avionics unit e.g. the TCAS display or a radio control box. But how then can you accurately assess the pilot's workload and the effect this may have had on his performance? This problem has increased in recent years because of the number of different variants of a particular aircraft being offered by the aircraft manufacturer and has been compounded by the emergence of Flight Training Centres who cater for a number of different customers with dissimilar aircraft. For example, each different engine fit results not only in different performance characteristics but also potential aerodynamic variables due to the engine cowling/pod design. Additionally, modern 'fly-by-wire' aircraft employ sophisticated avionic units in their control systems. These units are populated with both 'firmware' and 'software' that can be and frequently are modified, both during aircraft development and whilst in service. To ensure that the concept of the use of flown data for simulator validation remains inviolate would require that the aircraft manufacturer retains an instrumented test aircraft, in each configuration, available at all times: this would clearly be financially unacceptable. Therefore, the aircraft and simulator manufacturers have proposed that, so long as one set of original data is based upon aircraft tests it is possible to substitute alternative data for the variant models. The most commonly accepted substitute is the use of engineering simulator data. The problem is that these same regulatory bodies that are supposed to approve the use of the substituted data are often not staffed with personnel capable of monitoring the validity of this computer-generated data. But even more fundamental problems can occur during the lifetime of an aircraft. For example, the Jetstream 31 aircraft was originally designed and entered service with a 4-bladed propeller driven by a 900 shp Garret engine and the associated simulators used the appropriate data for both qualification and approval. However, the same aircraft finished its life with an engine producing 1,020 shp but this has never been incorporated into the simulator. Any investigation into an accident involving engine malfunctions or any handling qualities assessment would clearly be affected by this change.

Summary

Flight simulation has become an indispensable tool for training within aviation and has established a reputation for high levels of fidelity. Flight simulation has also proven itself to be an invaluable tool for the accident investigator but the seductive level of 'fidelity' might lead the unwary investigator to draw invalid conclusions. In order to reduce the possibility of this occurring the investigator needs to follow a simple plan.

Consider carefully what is required from the simulator assessment. Flight simulators are good if you need to understand the sequence of a systems malfunction, or the manner and rate at which information is provided to the pilot, although this may not be true of an older flight simulator. They are also excellent for evaluating the time frames at which events occur; at least we can then begin to appreciate the problems facing the pilot. However weaknesses exist relating to both the motion and visual cues, and particularly their integration. The detailed modelling on which a simulation is based may also be imperfect and it would be wise to develop a clear understanding of the precise nature of the physical differences between the particular aircraft and the chosen simulator. Any excursion from the cleared flight envelope should be considered a 'best guess', because that is all that it is, and be very careful with any workload assessment.

Having considered what is required it is then necessary to discuss the detail of the assessment with both the simulator manufacturer and the aircraft operator. The manufacturer will understand the simulation issues and, when prompted with the correct questions, will be able to explain their limitations. The operator will be able to explain the standard operating procedures and how their training is conducted. For example, how were their pilots taught that a certain system worked? How does this correlate to the simulation of that system? How were their pilots taught to respond to a particular malfunction? With answers to these questions it is probable that valid conclusions can be drawn from the simulator assessment and the best use will have been made of this unique investigative tool.