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ORIGINAL PAPER

Evaluating an Aircraft Response to Disturbances Caused by Vibration Frequency of Wind Forces During Landing

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ABSTRACT

Approach and landing phases take less than 4% of total flight time of a typical flight, but 36% of fatal aircraft accidents occur during this phase. Gust disturbances creating uncertainties during this phase are primary contributors to many unstabilized, high and fast approaches leading to catastrophic ending. This study analyses the effects of gust and resulting responses affecting the handling and flying characteristics of an aircraft during landing. A pilot-in-the-loop flight simulation during landing with the effect of gust was developed using Boeing B747-100 aircraft to analyze the problem. Elevator and throttle inputs through a joystick were used as control inputs to allow the pilot-in-the-loop to control the aircraft glide-path and speed during landing. It was found that the aircraft flight path during the descent is not affected, if the frequency of the gust is higher than the natural frequency of the aircraft, but maintaining the flight glide path becomes difficult for lower frequencies. Likewise, the vertical gust has more prominent effect than the horizontal gust. In both cases, the aircraft susceptibility to gust disturbances increases the pilot workload causing more difficulties for a landing.

Keywords: Airline; Aviation; Flight; Flying; Glide; Gust; Pilot.

INTRODUCTION

An unstabilized approach to land an aircraft may result in the aircraft reaching the runway threshold too high, too fast, out of alignment with the runway, or wrongly configured making an unsafe landing. This type of landings may result in damage to the aircraft, injury to its occupants or destruction of airfield. Therefore, continuing an unstabilized approach is the main factor in 40% of all landing related accidents (Airbus 1998). Though the landing phase consists of approximately 4% of a typical flight time, about 36% fatal heavy aircraft accidents occur during this phase of a flight (Boeing 2020). One of the contributory factors of unstabilized approach is adverse weather, such as strong or gusty winds, wind shear or turbulence (Flight Safety Foundation 2000). The atmosphere is never completely at rest and its primary parameters vary with position and time. Consequently, it is difficult to precisely quantify the atmospheric parameters. Similarly, detecting them is also difficult, because their nature and occurrence are random (Etkin 1981).

Wind gustiness is one of the risk factors during landing operations. Unexpected and sudden changes in wind speed and direction are critical to aircraft in flight particularly when flying at low altitudes and low speeds (Thompson *et al.* 1935). Effect of

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wind turbulent is an important issue in addition to several other reasons. For example, interaction of an aircraft with turbulence causes dynamic response to the aircraft and its structure. It affects the aircraft controllability and ride quality for passengers. Likewise, during landing, the turbulence increases difficulties in maintaining flight path accuracy, which is a prerequisite for landing maneuvers. Therefore, aircraft response to turbulence affects the aircraft structural loading, passenger comfort and flightpath. Consequently, researchers have done many theoretical and practical investigations on this subject. However, it is still problematic to describe with sufficient accuracy the dynamical model and the behavior of an aircraft motion in gusty condition during landing.

Landing phase is the most dangerous part of an aircraft operations. This is the stage when status of the aircraft changes from airborne to ground. Due to dynamic nature of the aircraft, it is difficult to predict the aircraft performance caused by aerodynamics uncertainties that are coupled with external disturbances during landing. As this critical maneuver takes place near the runway and when the aircraft is flying at a low speed and low altitude, it is considered as a high-risk task. A typical landing phase consists of airborne segment and ground segment. To accomplish a successful landing, the main longitudinal criterion during the airborne segment is to maintain a constant glide path angle, which is normally 3° while maintaining a constant approach speed of 1.3 times the stalling speed (Vs) and a constant rate of descent up to the flare height. The presence of gust in the form of updrafts or downdrafts during landing usually tends to alter these parameters.

To regain the required value of both flight path and speed on the longitudinal flight path, the pilot must make quick adjustments to the pitch angle and power setting. The situation befalls very critical in the last few hundred feet height as the aircraft moves toward the runway touchdown zone. Errors in handling may either lead the aircraft to land short of runway, attempt hard landing or overshoot the runway. Successfully managing this situation depends on severity of wind conditions, aircraft performance and pilot skills. Pilots sometimes tend to misjudge or overreact to effects of the gust. This at times upsets the stable pilot-aircraft system that leads to pilot induced oscillations (PIOs) (Turkel and Frost 1980).

Therefore, this study examines the effect of turbulence in the form of gust with different frequency and amplitude during a manual landing of an aircraft with a human pilot in the loop in the longitudinal plane. The overall purpose of this paper subsequently is to explore the effect of environmental disturbances and aircraft response with a pilot-in-the-loop during a manual landing. The primary focus is to examine the effect of gust on aircraft longitudinal motion during the landing phase with the pilot in the loop and manual thrust control. Gust modelling and pilot input are required for this analysis.

A qualitative study using a flight dynamics engineering simulator integrated with the Flight Gear Open-Source Flight Simulator was also carried out. The Flight Gear simulator provides visualization and realism of flying by providing an out-of-the-window view to the pilot. No comprehensive and quantitative criteria have yet been developed to provide a basis for the objective evaluation of the behavior of the aircraft in wind, gust, or turbulence as a function of its frequency and amplitude. Therefore, this study focuses on the reaction of pilot-aircraft system to a gust input during landing.

Both horizontal and vertical gusts have a slightly varying effect on the aircraft dynamics in the longitudinal plane. The variation in aircraft speed and altitude due to vertical gust is more pronounced than the effect of horizontal gust. Elevator input therefore has more effect on the aircraft dynamics. The throttle mainly affects the horizontal speed initially and then slowly changes the altitude. When higher frequencies are used, their response slowly diminishes, and reverse effect starts to take place. Likewise, lower or higher gust frequency and the aircraft natural frequencies have different effects on the aircraft response. This requires different control techniques to control the aircraft. Therefore, the study leads to believe that lower frequency vertical gust has more pronounced effect on the aircraft forward speed and flight path as compared to the horizontal gust. Hence, a lower frequency vertical gust requires immediate and accurate corrective action by the pilot during approach and landing phase.

WIND MODELLING AND PILOT-VEHICLE DYNAMICS

Initial studies on atmosphere turbulence were carried out to predict its behavior. New methods are developed to characterize the atmospheric turbulence, estimating the parameters of these characterizations using modern statistical methods, and computing relevant aircraft response statistics to the turbulence (William 1981). Practical experiments using the Boeing 747 aircraft to collect wind-shear data from various parts of the world were carried out (Woodfield and Wood 1981). As a result, time histories of wind velocities and aircraft response were identified and analyzed. Based on the wind data, the aerodynamicists were able to estimate the dynamic response of the aircraft during landing in gusty conditions especially with a windshear (Frost *et al.* 1985; Frost and Reddy 1978). Similarly, Shao *et al.* (2010) concluded that the proposed control system could effectively alleviates random gusts. However, these researchers did not consider the involvement of pilot in the loop, nor did they provide any insight into the effect of varying gust frequency and amplitude on aircraft response. Consequently, literature does not present any effective technique that can be used by pilots during approach and landing in gusty conditions.

Two obstacles that confronts aircraft landing are poor visibility and turbulent air. Modern navigation techniques have solved the problems related to visibility. However, the turbulent air continues to be a deterrent. Wind hazards confront an aircraft in the form of windshear, jet streams, mountain waves, convective thermals, warm-cold air mass fronts, sea breeze fronts and terrain-induced turbulence due to irregularities of the Earth's surface, such as vegetation and urban development. In the earth boundary layer at approximately 2000 feet above ground, the mean wind decays toward the ground and it has considerable horizontal variations due to irregularities in terrains. The mean velocity profile over a surface is approximated by the seventh power law (Eq. 1) (Lawson 2001).

$$\frac{V}{V_{ref}} = \left[\frac{z}{z_{ref}}\right]^{\frac{1}{7}} \tag{1}$$

where, z is the height above surface and V is the wind velocity.

Turbulence motion is difficult to visualize and predict, but some spatial organization to the motion can be noticed by observing smoke. The turbulence is neither a stationary, gaussian or isotropic. So, its random motion is described by statistical properties (Greene 1979; Nelson 1997). Turbulence velocity is a random vector function of position r and time t similar to its magnitudes and frequencies of occurrence (Eq. 2).

$$w_0(r,t) = w_0(r,t) + \Delta w(r,t) \tag{2}$$

where w_0(r,t) characterizes a measurable component persists over time and region, while the statistical properties of Δw(r, t) may be relatively constant (Stengel 2005). Δw(r, t) is a random process which components are characterized by probability distributions.

In early aeronautical work, turbulence was described in a form of discrete gust mainly to determine the structural limit designs load factor calculations for the worst-case scenarios (Etkin 1981). The discrete gust has evolved to currently favored (1-cosine) as specified in the FAR 25 airworthiness requirements (Panofsky and Dutton 1984; McLean 1990). Later, continuous atmospheric turbulence models emerged. Two mostly accepted models are the Dryden model and the Von Karman model (Department of Defense 1980). Both use the power spectrum density (PSD) approach expressed in frequency domain and they are difficult to use in the flight dynamics equation (Smith and Adelfang 1998). The Von Karman model is least favored in analytical studies, because it has a more complicated PSD function. As the non-integer index is not easily modelled in state space, this model is difficult to simulate, directly (McLean 1990). The Dryden model PSD function is simpler and easier to program.

Atmospheric turbulence varies widely and there are few turbulence models in use, currently. However, no analytical expressions can completely describe these atmospheric disturbances. They are either inconvenient or difficult to use due to their complexities in integrating the model into the equations of motion (EOMs) (Fred *et al.* 2000). In absence of any standard model, a simple sinusoidal wave contains all the pertinent parameters of a wind gust can be injected to evaluate the response. This simplifies the mathematical modelling calculations and analysis. Furthermore, the sinusoidal wave input is easy to control, manipulate and gives an acceptable result, which can be traceable for engineering analysis. Even the fundamental spatial frequency Ω in the Von Karman and Dryden PSD consists of a sinusoidal component. Additionally, any arbitrary gust can be presented by in the form of sinusoidal wave using Fourier analysis, if required (Nelson 1997).

Aircraft are designed with some degree of inherent stability. Consequently, if they are disturbed, they will tend to come back to their initial path without any pilot input. However, the frequency of disturbances and damping are vital in the evaluation of aircraft flying and handling qualities. With an unstable short period, it is mostly very difficult for the pilot to control the aircraft (Islam *et al.* 2016). It will give a very uncomfortable ride to the pilot and passengers. With its natural short period, the oscillation may get worse, if a pilot attempts to reduce it by a flight control input. The oscillation may go out of phase due to slow reaction time by the pilot. There is also a risk of PIO, which may eventually lead to destructive coupling condition (Chapa 1999). When lightly damped, the aircraft becomes dangerously unstable and uncontrollable, sometimes.

In most cases, after damping the short-period the long-period-low-damped phugoid oscillation produces slow changes of speed and height. As the damping is very weak, the period is approximately 40–100 seconds long for a large aircraft depending on the aircraft parameters, configuration, and flight conditions (Etkin 1972). The pilot usually can correct this motion by small control movement without being aware that the oscillation even exists. It can be corrected easily, but it increases the pilot fatigue in case of low damping. This is normally not a serious problem because the speed and altitude changes are not large and the duration is short. While flying in visual metrological conditions (VMC), the phugoid frequency and damping can vary largely, but the aircraft is still acceptable for a flight. However, during instrument flying, low phugoid damping becomes the objective (Nelson 1997).

The degree of damping and frequency of oscillations can be determined by aircraft geometric and aerodynamic properties with corresponding effect on the aircraft performance (Fig. 1). For example, increasing the tail area will augment both static stability and the short-period oscillation damping, but it will increase the aircraft weight and drag (Nelson 1997). Figure 1 shows the main criteria for both the dynamic modes.

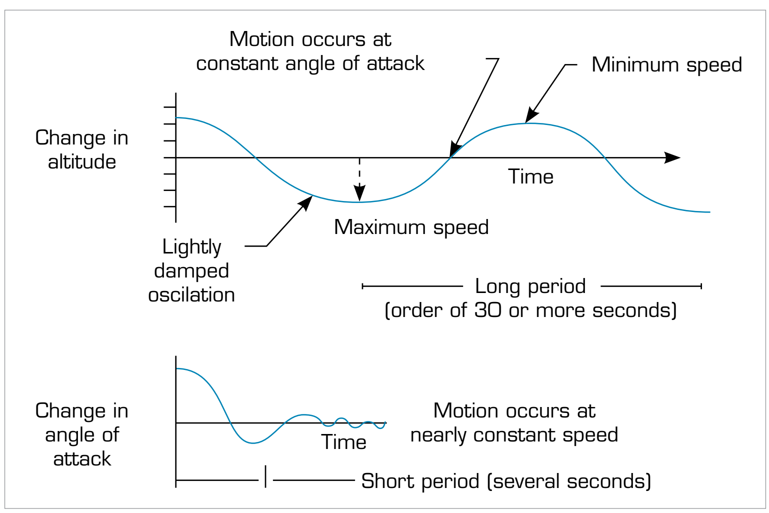

Figure 1. Phugoid and short period motion. (Nelson, 1997).

Early researchers of flight dynamics predicted the longitudinal and lateral motions, but they could not interpret their findings, because when their findings indicated that the aircraft would be unstable, the aircraft was flown smoothly. This makes them wonder how their stability analysis could be used to evaluate the aircraft design quality. Finally, it was realized that the missing factor in aircraft stability analysis was the inclusion of pilot as a vital part of the aircraft system (Nelson 1997). Similarly, in a manual flight, the pilot and the aircraft flight control system collectively comprise a man-machine system (Fig. 2). This forms a closed-loop feedback control system. Therefore, in a pilot-vehicle system, the process of pilot detection and control can be divided into three different types known as compensatory control, pursuit control and precognitive control (McRuer 1973). In the compensatory mode, the pilot senses an error between a desired configuration and the actual aircraft configuration and then provides corrective action to minimize the error. Once the pilots become completely familiar with the aircraft response characteristics, they can generate smart, discrete, properly timed, and sequenced outputs of flight control under certain conditions that result in desired aircraft responses. These highly skilled movements are learnt and practiced by pilots.

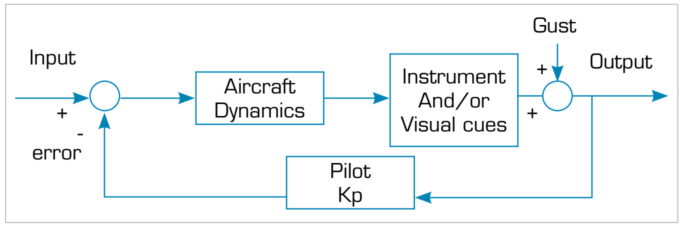

Figure 2. A pilot-in-the-loop system. (Elaborated by the authors).

Aircraft handling and flying qualities are closely related to aerodynamic properties of the aircraft, atmospheric disturbances and pilot actions to do a flight task in a safe and efficient manner (Fig. 3). PIO is a matter of concern for aircraft handling issues. PIOs are continual or uncontainable oscillations resulting from the pilot's action to control the aircraft (Department of Defense 1990). They appear when the aircraft begins to divert from desired flight path and the pilot applies inappropriate, excessive, or miss-timed corrections. These phenomena happen when a vicious circle is formed between the pilot and the given control input due to a triggered event. The excitation transmitted from one to the other is being continuously reinforced. They can develop from external or internal inputs including wind gusts (Hodgkinson 1999). This aircraft-pilot-coupling event is inadvertent. Simply, it is a result of mismatch between pilot input and aircraft response. The oscillations may be temporary, easily corrected, having low-amplitude, or a fully developed large-amplitude that can lead to near or actual catastrophic consequences jeopardizing the safety of the aircraft. PIO events usually occur when the pilot is busy in a closed-loop control tasks, such as approaches and landings. PIOs can be eliminated by loosening the control (Mitchel and Roger 1995). Since it is difficult to describe analytically with accuracy, experiments are required using trained pilots to understand the real system dynamics. A combination of ground and in-flight simulators provides engineers with an effective tool to do systematic assessments of aircraft handling qualities (Department of Defense 1980).

There are many advantages of using flight simulators. Besides being cost effective, it is also safe to carryout maneuvers that can otherwise be dangerous using a real aircraft. Equations of motion are the nerves of flight simulators. They are used to generate the states of the simulator using inputs to compute the variables representing the state of the simulated aircraft (Fig. 4).

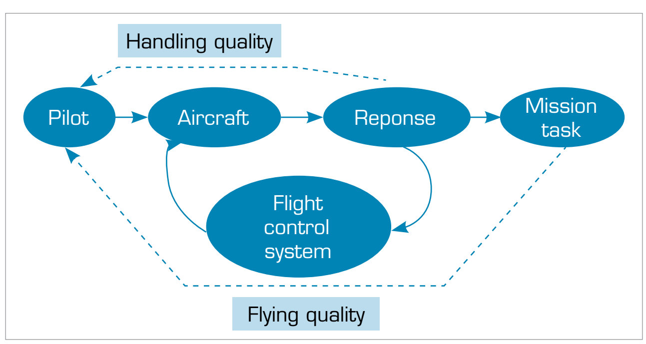

Figure 3. Flying and handling qualities of conventional aircraft. (Elaborated by the authors).

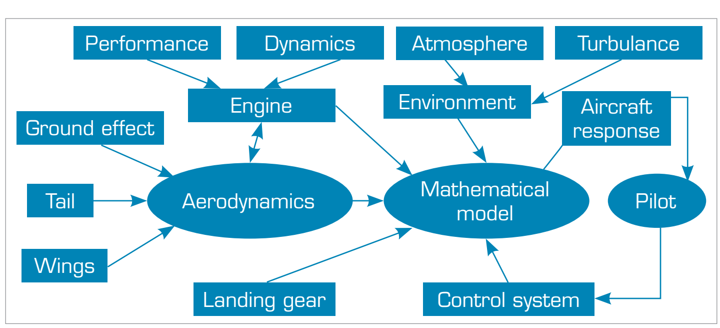

Figure 4. Components of modelling a flight simulator. (Elaborated by the authors).

METHODOLOGY AND DATA COLLECTION

This study had used linearized EOMs to represent the dynamics of the aircraft, and the simulation was carried out using a fixed-base flight simulator. Consequently, EOMs are derived by the linear and angular aerodynamic forces and moments acting at the center of gravity of the complete rigid aircraft. The linearized, body axis, decoupled and small perturbation theory are used to derive the EOMs of the aircraft. The small perturbation equations are linear equations derived from non-linear equations, algebraically. In these equations, the aerodynamics coefficients are replaced by terms involving the aerodynamic derivatives (Stevens *et al*. 2016). The advantage of the small-perturbation equations is that the aerodynamic equations can be estimated quickly before nonlinear data becomes available. Additionally, it provides a clearer picture of the relative importance of the numerous aerodynamic derivatives at different flight conditions and their influence on stability of the aircraft (Stevens and Lewis 2003). Only the longitudinal motion is considered for this study. A four-engine Boeing 747-100 large jet transport aircraft operating at sea level on approach configuration with full landing flaps and gear-down is chosen as the representative aircraft for this research.

The stability coefficients consist of the aerodynamics and control derivatives in addition to mass and inertia properties of the aircraft. Derivation of the complete EOMs was done with inputs from elevator control, thrust control and gust input values (Fig. 5). To represent the aircraft at a point in time, state and control variables are required. The state variables itself completely describe the state of the aircraft. Control variables are the inputs to the simulation, either from flight control surfaces input (elevator in this case), thrust input or external disturbances, such as gust. These are given in the form of stability derivatives, and they are functions of Reynolds number, Mach numbers, aircraft configuration and body mass, and environmental conditions. The dimensional stability derivatives values for the state and control vector are taken from a study carried out by McLean (1990) using a very large four engine passenger aircraft. Similarly, for the aircraft flying and handling quality study with gust in the landing phase, additional variables including height, flight path angle and angle of attack are required to obtain complete response characteristics. This is done by expressing it as a function of the basic aircraft motion variables and/or by supplementing the state depiction of the aircraft in the state space matrix. Likewise, for the height variable, a new state variable must be created to expand the state equation. However, the angle of attack and flight path angle are expressed as the sum of basic aircraft state variables by having two additional output variables and augmenting the output equation accordingly.

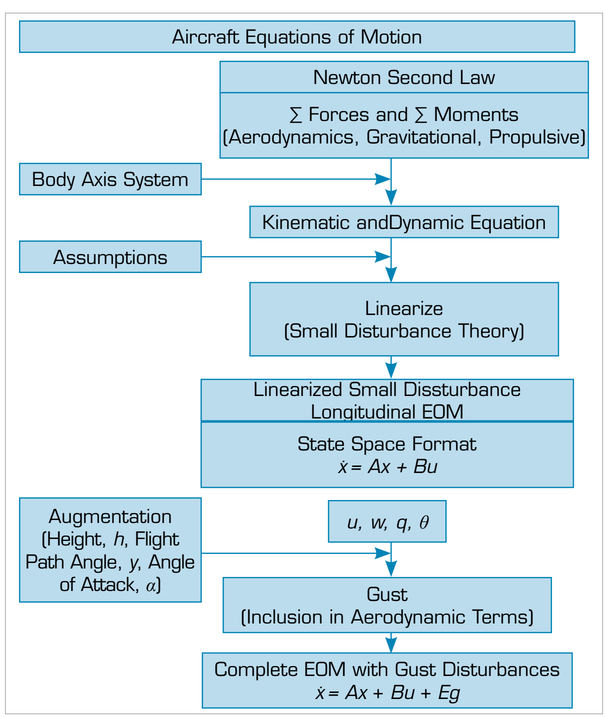

Figure 5. Flowchart of the derivation of equations of motion with gust effect.
(Elaborated by the authors).

Interaction of the aircraft system aerodynamics with the gust results in forces and moments being developed, which in turn cause aircraft dynamic response. Most importantly, it affects the accurate maintenance of flight path, which is a prerequisite during landing. Generic research provides a complete development procedure of the general EOMs, but the variation of wind gradient is not integrated into the equations, because wind is assumed as zero or constant. As such, the aircraft dynamics are assumed to be linear about the trimmed flight condition and invariant with time (Abdulrahim *et al.* 2010).

In order to introduce gust into the mathematical model, alterations are needed, because wind affects the aerodynamic forces and moments. Both vertical and horizontal gust are analyzed, but to keep the simulation simple, only the vertical gust that alters the longitudinal flight path was simulated. The mathematical model with the gust disturbance in the vertical Wg and horizontal Ug are combined with the original EOMs. Both gust disturbances are represented as a sinusoidal wave form with varying amplitude and frequency while the atmosphere is considered as frozen in space when the aircraft transits the region. The turbulence input is modelled by a deterministic form, which is a sinusoidal wave for numerical analysis and continuous form during the flight simulation. After inclusion of the gust, the complete equation becomes as Eq. 3:

$$x = Ax + Bu + Eg \tag{3}$$

Where, x = state vector; u = control vector; g = gust disturbance vector; A, B and E = aircraft dimensional stability derivatives in a matrix form.

Beside aerodynamics, which is a major contributor to the forces and moments on an aircraft, the propulsion does contribute as well. Consequently, the thrust input is used to determine the effect of thrust variation on the aircraft motion (Fig. 6). This is achieved by applying the thrust input once the aircraft is in trimmed condition. The thrust generally excites the phugoid mode only.

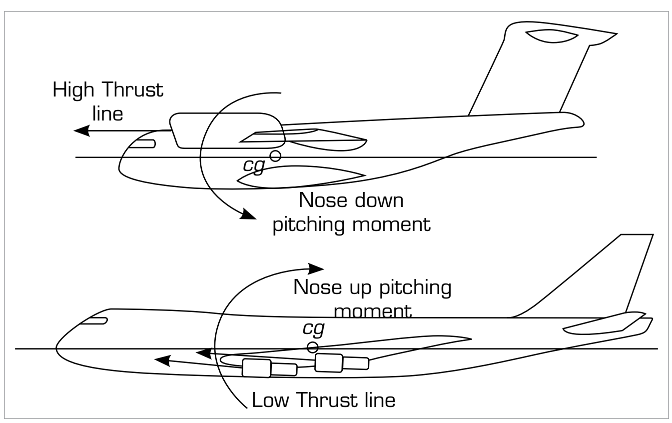

Figure 6. Effect of thrust on two differently mounted engines. (Elaborated by the authors).

Likewise, the state space modelling is a powerful and a convenient method being used as a machine solution of the EOMs. The obtained solution helps to simplify the analysis of aircraft dynamics. The model of the aircraft longitudinal motion is multiple-input multiple-output (MIMO) system with two inputs from elevator and engine thrust and seven outputs from horizontal and vertical velocity, angle of attack, pitch angle and pitch rate, altitude, and flight path angle. In state space format (Eq. 4):

$$\text{Input eqution: } \dot{x} = Ax + Bu + Eg$$
$$\text{Output equation: } y = Cx + Du \tag{4}$$

Where, A = state matrix, B = control matrix, E = disturbance matrix, C = Output Matrix, and D = direct (null) matrix.

The short and long-term effects of elevator and thrust responses are quite different. Longitudinal control and the transient that connects the initial and final responses can be observed from a time response analysis. This includes the short-period heavily damped oscillation and the long-period lightly damped phugoid oscillation. Time response analysis is essentially the response of a system variable over a period of time. When the transient effect of the elevator and thrust responses finally die out, a new steady state condition takes place. Likewise, a system frequency response analysis is fundamentally an input-output magnitude ratio and phase relationship over a selected frequency range of interest. The output has the same frequency as the input, but with its magnitude and phase responses changes as a function of the individual system characteristics. The specific magnitude and phase relationship is intimately a function of the input frequency of the exciting system where the input is a periodic sinusoidal waveform with the output having the same sinusoidal frequency with changes in magnitude and phase. The frequency analysis also allows the closed loop system behavior to be analyzed using the open loop system. One way of presenting this input-output result is by Bode plots where magnitude is in decibels (dB) while phase shift in degrees against log-frequency. The extracted output response frequency follows a linear model approximation where the actual aircraft dynamics are nonlinear. Due to that limitation, this analysis is limited to small amplitudes variations known as small perturbation about a trimmed flight condition. Hence, the frequency response analysis approximates the aircraft dynamic characteristics of the input-output relationship with a linear model in the frequency domain. Considered inputs are from the elevator, thrust and gust both vertical and horizontal, whereas the output of interest are the forward speed and height variations.

This study uses the open-loop analysis to examine the effect of both elevator and thrust controls and the gust (Fig. 7). This has been carried out independently by isolating them from the effect of the other parameter. However, the closed-loop analysis is used with the effect of control, gust and the pilot input for the simulation (Fig. 8). B747-100 aircraft derivatives are used in the research. Using MATLAB, the phugoid and short periods are calculated. The results of the plots and calculation are then compared with the simulation using the EOMs and the estimated periods (phugoid and short period) from the plots. EOMs are then used for the simulation. The simulation basically operates by solving the aircraft EOMs continuously in a loop. The equations therefore must be rewritten in the form of full equation from the state space format in order to use for the flight simulation.

Flight simulator joystick (control column) was connected to the MATLAB/Simulink program to achieve the pilot-in-the-loop simulation and a MATLAB program was written to convert the analog input to digital. In Simulink, a blockset is readily available for the joystick connection. Two different types of elevator control were used depending on the pilot's preference. It was expected that the pilot flying Airbus type aircraft would prefer the joystick while the pilot on Boeing type aircraft would prefer the conventional control column.

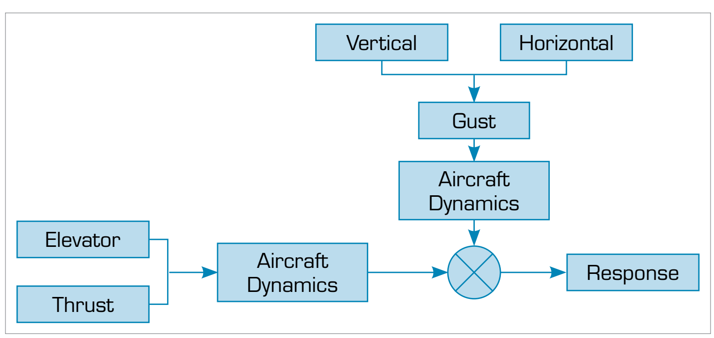

Figure 7. Open loop analysis. (Elaborated by the authors).

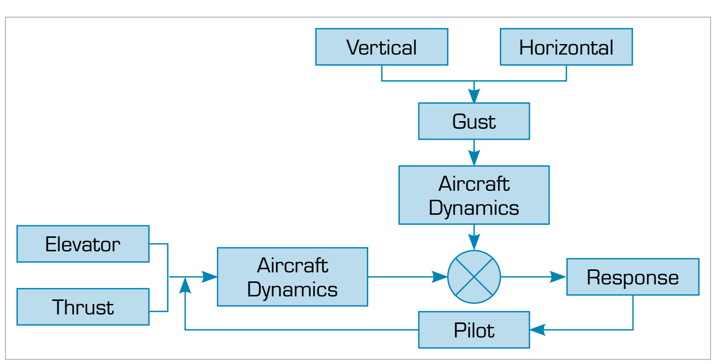

Figure 8. Closed loop analysis. (Elaborated by the authors).

A flight test was then carried out using a fixed-based flight simulator (Fig. 9). The primary purpose of the flight test was to establish the gust effect during the aircraft landing and as an initial evaluation of the simulator and pilot-aircraft interactions. There was no discussion prior to the trial as to how the aircraft might behave, nor of what action the pilot should try to take. Before the experimental portion of each trial, each pilot was given a learning period to become accustomed to the environment of the simulator and to the handling characteristics of the represented aircraft. The actual trials were not started until the pilot became conversant with the system and the simulated aircraft responses to the controls. The learning period lasted around 20–30 min for both pilots, separately. The pilots were informed that they would experience variable wind conditions, but they were not made aware about the type and acuteness level of the winds. Each trial lasted for 20–25 min. During this time, the simulated aircraft was subjected to calm wind and two different types of continuous random disturbances (gust) representing atmospheric turbulence with varying frequency and amplitude. After each run, the pilots were requested to comment on the turbulence intensity, realism and workload, and to provide a Cooper–Harper handling quality rating. In addition, the pilots were also requested to evaluate the altitude, terrain, and atmospheric stability. Two airline pilots with large commercial aircraft experience had carried out the flight test. Pilot 1 is 40 years old, holds an airline transport pilot license and type rated on Airbus 310, 340, Boeing 777 with 9000 hours of total flying experience. Likewise, the pilot 2 is 36 years old and holds an airline transport pilot license type rated on Airbus 330 and Boeing 747-400 with 7000 hours of total flying experience. The pilots were provided with initial and final briefings before commencing the test.

Initial briefing: You are flying a large four-engine jet transport aircraft at 4000 feet. The aircraft is in trimmed level flight with autopilot engaged until the simulation is started. The position is approximately 15 nautical miles from runway 32R Kuala Lumpur International Airport. Manually fly the aircraft and start descending on the 3 degrees glide path when required. For guidance, a graphical display of the descend guidance is available. At touchdown, the simulation terminates and evaluation ends. The flight is in visual metrological conditions. It is known that there is thunderstorm activity in the nearby and the wind may change. Try to fly the aircraft under these conditions using appropriate operating techniques.

In the final briefing, the pilots were introduced and explained about the aircraft dynamic modes and the effect of gust and thrust delay to the aircraft response. The suggestion as not to over-control when flying during the high frequency gust and a quick response during the low frequency gust was given. Some aspects of PIO were also explained and discussed with them. Pilots were also introduced to the Cooper–Harper rating scale and its uses. They were also encouraged to ask any other doubts and clarification at any time during the flight test.

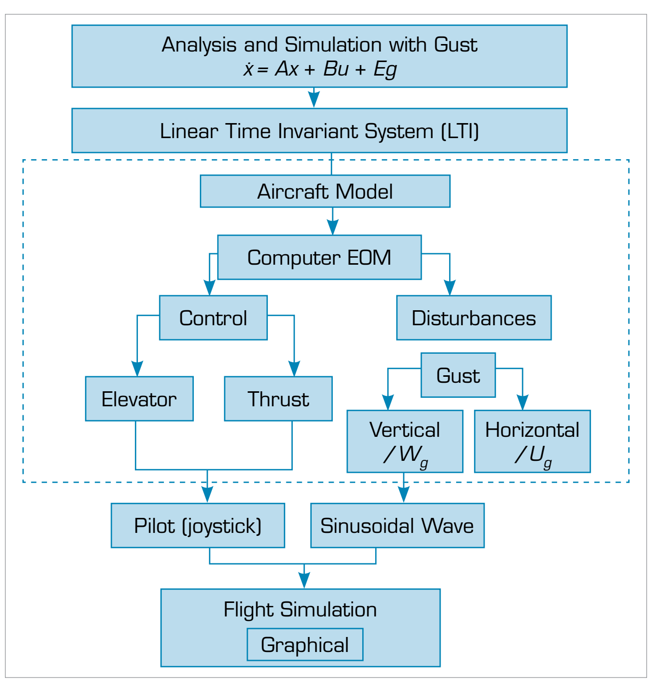

Figure 9. Overall research flow chart. (Elaborated by the authors).

RESULTS AND DISCUSSION

A stable approach to land depends on the relative airflow on aircraft wings to create lift and to keep the aircraft in trim condition on a desired constant glide path. A disturbance changes the relative airspeed and balance of forces, and it creates an out of trim condition affecting the flight path. It may be originated by the pilot using control inputs, changing aircraft configuration, different power settings, or by external disturbance such as gust. Both the longitudinal dynamic stability modes (short-period and phugoid) are excited by the disturbance. Consequently, the phenomenon if not corrected quickly can lead to a hazardous situation since the pilot reaction-time and engine acceleration-time become relatively smaller as the aircraft advances towards the runway touchdown point.

Static stability is a requirement for a human pilot to control an aircraft in longitudinal plane without excessive attention or strength. An aircraft with positive longitudinal static stability is easy to fly and maintain the desired pitch attitude that helps to control aircraft speed, flight path angle and height, subsequently. Positive static stability property of an aircraft also assures that the aircraft will return to the equilibrium state by itself, if disturbed by gust. The aircraft selected for this study is both statically and dynamically stable. The elevator, thrust and gust inputs have different effects on the aircraft dynamics. An impulse input excites the short period mode (vertical speed w, angle of attack α and pitch rate q) while the step input excites the phugoid mode (forward speed u, pitch angle θ, height h and flight path angle γ). These different inputs are used to verify the aircraft short period and phugoid characteristics. Similarly, the different gust frequencies also affect the aircraft response differently. The forward speed and height changes are negligible at higher horizontal and vertical gust frequencies than the aircraft short period frequency. However, when the gust frequency is lower than the phugoid frequency, both forward speed and height perturbation are increased. This could affect the aircraft handling during the approach. The aircraft response due to vertical gust speed is more dangerous than the horizontal gust as the aircraft will always be below the flight path. When the gust amplitude is increased, the forward speed and the height also mostly increase. This increase is more significant with lower gust frequencies though.

Figures 10, 11 and 12 show the pilot-in-the-loop input flight path response plots for three different vertical gust conditions set for nil wind, high frequency (1 Hz) and low frequency (0.07 Hz) while the gust amplitude is 10 m/s. The actual path flown is overlapped over the predefined approach path and the 3 degrees glide slope. For the nil wind condition, following the flight path on level segment and the 30-glide path do not pose any difficulty (Fig. 10). The deviation from the defined path is very little except the portion when the simulation was started. This is mainly due to the insufficient elevator input. Once the pilot gave sufficient elevator input and chosen the correct thrust setting, the rest of the approach becomes easy. There was a difficulty until intercepting the glide path for the approach in high frequency gust condition (Fig. 11). Once the pilot is familiar with the handing and the descend portion commenced, it was relatively easier to follow the glide path with small deviation above and below the path. However, Fig. 12 presents very different result as compared to the previous two conditions. Flying the approach in lower frequency vertical gust condition has significant effect on the flight path control and flight path deviations. Furthermore, the flight path mostly remains below the defined path. Just before touchdown, large corrections (nose up elevator pitch and thrust increase) brought the aircraft well above the glide path that ended up in long touchdown well beyond the safe touchdown point.

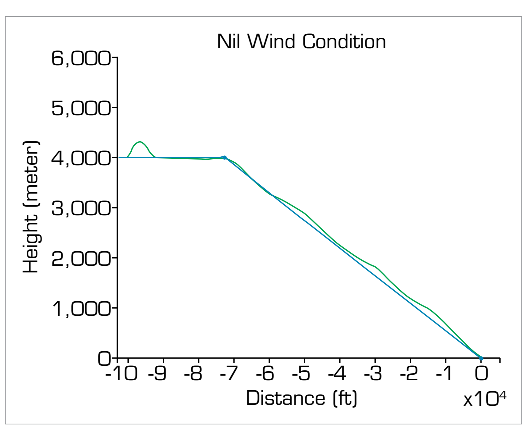

Figure 10. Flight path control in nil wind condition following the predefined glide path. (Elaborated by the authors).

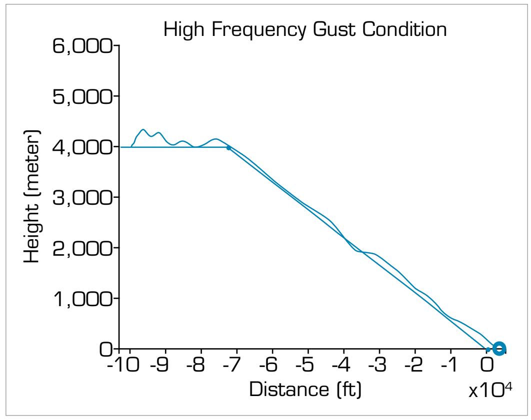

Figure 11. Flight path control in high frequency vertical gust condition following the predefined glide path. (Elaborated by the authors).

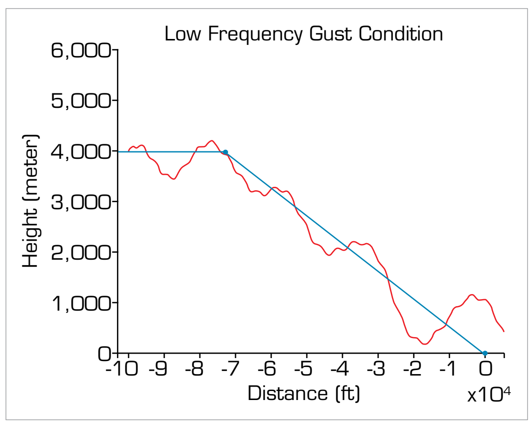

Figure 12. Flight path control in low frequency vertical gust condition following the predefined glide path (Elaborated by the authors).

Both pilots reported that the thrust delay response due to thrust increase was similar to a jet engine response experienced in actual operations. They did not have any problems anticipating this engine characteristic. They also commented positively about the aircraft response after conducting general handling maneuvers including climb, descend, turning, accelerate and decelerate. Pilot 2 having flown the Boeing 747-400 type aircraft commented that the aircraft handling and response was like the real aircraft.

For nil gust named as condition 1—after initial and final briefing, the gust parameters before and after final briefing were similar. For both pilots, the approach performance of tracking the centerline and maintaining the glide path was virtually a simple task. There was a slight difficulty during the period of after-initial-briefing. However, it was much easier later, because they are more familiar with the simulator and the approach, especially after flying in the gusty conditions. Nevertheless, both commented that the simulation lacks realism as the condition was too calm (no wind) although thunderstorm was reported. They also had some problem in judging and crosschecking the distance and height to touchdown due to poor simulation cues. Lack of motion cues also caused difficulties for them to estimate the touchdown time and exact location, because they were not able to feel the sink rate of the aircraft before and at touchdown. Overall, the results obtained are satisfied for nil wind condition and their Cooper–Harper ratings were similar for both the attempts (Table 1).

Table 1. Rating for the Condition 1 – nil gust, after initial and final briefing.

Pilot	Condition 1 – after initial briefing	Condition 1 – after final briefing
1	4	2
2	4	2

Generally, the gusts introduce additional aircraft dynamics and increases pilots' workload, requiring more manipulation of both elevator and throttle controls. Consequently, the pilots' evaluation was almost opposite of what they said with nil wind condition. The flight with gusts was simulated with four conditions. Firstly, condition 2a – after initial briefing, where the gust was set at a higher frequency than the aircraft short-period frequency. Secondly, condition 2b—after final briefing, where frequency and amplitude remain same as the condition 2a. Thirdly, condition 3a—before final briefing, where the gust was set at a lower frequency than the phugoid frequency of the aircraft. Finally, condition 3b—after final briefing, where frequency and amplitude remain same as the condition 3a.

For the condition 2a, the gust of 1 Hz and amplitude of 10 m/s were used. Pilots noticed a slight disturbance as compared to the Condition 1. However, they were not able to predict the gust and they had very little problem compensating for that. It was a little more work than the nil wind condition. Pilot rating was little worse than that of nil wind condition. Their elevator and thrust inputs at times were not as normally expected. This implies that they were using wrong compensation technique to control speed and attitude of the aircraft to maintain the altitude. This was largely due to the misunderstanding of the frequency and aircraft response relationship. Also, they did not realize the delay in the thrust caused by spool up time of the jet engine after thrust input. Some features of PIO were observed. Pilots commented that the gusty condition (resembles) was missing during the nil gusts condition. Pilot 2 also mentioned that he could recall similar experience while landing an actual aircraft. However, for the condition 2b, it was observed that the flight path, speed and attitude control were better, but minute adjustments were made for deviations caused by the disturbances. Pilots looked confident controlling the aircraft and the rating was better (Table 2). However, pilot 1 commented that the continuous gust was not realistic.

Table 2. Rating for the condition 2a and 2b (high frequency gust – before and after briefing).

Pilot	Condition 2a – initial briefing	Condition 2b – final briefing
1	5	3
2	4	3

For the condition 3a, the gust frequency of 0.07 Hz and amplitude of 10 m/s were set.

The aircraft was seen trying to plunge up and down from the path, because the gust made the aircraft control task much more difficult. Controlling the aircraft speed and height apparently became difficult. Pilots stated that the aircraft had a tendency to pitch down and descend. The flight situation required them to increase the elevator input and constantly pitch up. On the final approach, the turbulence seemed to increase although the parameters remained same. This was due to the relative motion and more ground cues at lower heights. With their increased elevator pitch up inputs to avoid touching down before the runway, the aircraft crossed the runway threshold at a higher altitude leading to long touchdown. There was some form of PIO observed as the oscillation increasing and worsening just before crossing the runway threshold. Since the frequency was low, the pilots could not anticipate the gust as in the high frequency condition. They did not realize that quick correction was required as they were descending and the distance to touchdown was reducing. Rating given was 5 and 6, respectively. For the condition 3b, the gust characteristics and its effect, such as higher in amplitude and longer in distance due low frequency were explained to the pilots. They were advised to make quick and sufficient correction and maintain the constant attitude when close to the runway to avoid PIO. Both pilots were noticed to take appropriate action for quickly responding to regain the speed and flight path. Their threshold crossing height and touchdown point were also improved (Table 3).

Table 3. Condition 3a and 3b (low frequency gust – before and after briefing).

Pilot	Condition 3a – before briefing	Condition 3b – after briefing
1	5	4
2	6	4

Both pilots had a better control of the flight path and aircraft speed after the final briefing. Comments of Pilot 1 about continuous bumpiness with no periods of calm between the periods of bumpiness for Condition 2 is an acceptable observation. The pilots noticed that any usual infrequent large amplitude gust to force the aircraft away from the glide-path was missing in the simulated flight. Likewise, pilots' remarks suggested that the lowered ratings were mainly due to the risen workload to handle the disturbances. The important difference between conditions 2 and 3 with gust and with nil gust are that the pilots were compelled to aggressively control the aircraft throughout the approach. Their agreement and better understanding with the aircraft response and proposed control techniques seem more convincible than their unfavorable comments although the comments are true.

The result demonstrates that on a normal nil wind condition if the aircraft is above the glideslope, a reduction in engine thrust with slight pitch down is required to resume the initial flight path. On the other hand, descend from the glide path with a speed decrease requires a slight pitch up with an increase in thrust. However, the two cases present different issues to the pilots attempting to fly a glideslope during a gusty wind condition. Pilots tend to overreact in gusty conditions and complicated the matter. With high frequency gust, almost very minor changes in thrust and pitch are required. After many oscillations, the aircraft restabilizes at its original airspeed on the flight path. In low frequency high amplitude conditions, a quick reaction is required, because the time and distance to touchdown is limited. However, the most common pilots' error is, not making these corrections vigorously and rapids. An immediate recognition and response are required, especially at the last few hundred feet from the runway threshold. The delays in pilot's response and the thrust produced by the jet engines must also be taken into consideration, because these delays combined with both horizontal and vertical wind changes may end up in an unwanted situation.

CONCLUSION

Gusty winds have been a problem for flights since the beginning of aviation. There were many incidents and accidents related to this unfavorable atmospheric condition. Besides affecting the aircraft structure and passenger comfort it also makes flying and handling qualities of an aircraft a challenge. Various types of wind modelling have been done to study gust phenomenon in the past. However, the sinusoidal wave model is a good representative of an engineering gust model having the required parameters for input excitation and output response. Therefore, this paper is focused on the problem of gusty wind during landing which is the most critical phase of a flight. Gust and the thrust effect normally neglected in many analyses are included in the decoupled longitudinal EOMs. This study has found that a lower frequency vertical gust has more pronounced effect on the aircraft forward speed and flight path compared to the horizontal gust. Subsequently, the lower frequency vertical gust requires immediate and correct action by the pilot during approach and landing phase of the flight.

A qualitative study has been carried out using graphical simulation. The flight simulation helped to visualize and validate the effect of gust and established a practical *feel* of the problem. The qualitative study was done using two pilots with large jet experiences. Three flight conditions primarily with nil gust, high frequency gust and low frequency gust with before and after briefing were created. When flying in high frequency gust conditions, less or no input is found to be sufficient to maintain the flight path. However, during low frequency gust, an immediate corrective action is required. Both pilots reported that gust has an effect on their workload. They also performed better after the briefing with more positive control due to better understanding of the gusts effect. Most importantly, by introducing human pilot in the system and closing the feedback loop, the overall dynamics of the system got changed. The results show that a system with the combination of human pilot and aircraft coupled with the external disturbances is an intricate and complex issue especially during an approach to land. It is inherently difficult to examine the problem only by using the numerical methods. Qualitative study using experienced pilots therefore was necessary. In conclusion, this work has developed a simple engineering turbulence model for analysis and understanding of aircraft response dynamics, interaction between these parameters and the pilot-vehicle dynamic system during landing, including the handling quality and flying technique.

AUTHORS' CONTRIBUTIONS

Conceptualization: Kannan P; **Methodology:** Kannan P and Yadav DK; **Software:** Kannan P and Shuhaimi M; **Validation:** Yadav DK; Kannan P and Shuhaimi M; **Formal analysis:** Yadav DK; Kannan P; **Investigation:** Yadav DK; Kannan P; **Resources:** Yadav DK; Kannan P and Shuhaimi M; **Data Curation:** Yadav DK; Kannan P; **Writing - Original Draft:** Yadav DK; Kannan P; **Writing - Review & Editing:** Yadav DK; **Visualization:** - **Supervision:** Shuhaimi M; **Project administration:** Yadav DK; Kannan P and Shuhaimi M; **Funding acquisition:** -

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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