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Modeling U-2 Flight Through Clear Air Turbulence

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14. ABSTRACT
A dynamic three degrees-of-freedom simulation of the U-2 aircraft was developed in support of future Clear Air Turbulence (CAT) forecasting. Aerodynamic coefficients and the autopilot specification were obtained from the Lockheed Martin Aeronautics Company. The simulation used longitudinal aircraft equations of motion to model the aircraft's flight though CAT. The dynamics were modified to include non-steady relative wind conditions. Atmospheric inputs were created using wave models and other numerical simulations of CAT conditions. The results were compared to traditional turbulence sensitivity predictors, which appeared to under-predict the actual aircraft loads for some CAT conditions.

15. SUBJECT TERMS

Clear air turbulence	Gravity waves	High altitude turbulence
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1 Summary

Discussions with U-2 pilots have led to the realization that these aircraft, flying at their above-commercial cruise altitudes, frequently encounter a type of turbulence that is unique compared to what is considered traditional. The pilots describe two types of turbulence: 'mechanical' and 'mach surf'. The motion resulting from 'mechanical' turbulence was described as a somewhat random bumping in all directions. This is similar to the motion caused by the winds encountered by commercial aircraft. The motion resulting from 'mach surf', on the other hand, was described as more gradual changes in speed over time. The pilots have a temperature gage visible in the cockpit. During encounters of 'mach surf', pilots always notice dramatic changes in the temperature. These temperature changes alter the mach number of the aircraft, and the resulting speed changes from the autopilot elevator commands create the sensation of surfing the wave of temperature fluctuations. Pilots report that when the disturbances come at a wavelength of less than a mile, the effect on the aircraft is the worst, and can create a dangerous situation. A simulation was created to study this type of turbulence, and it suggests that traditional turbulence sensitivity design tools appear to under-predict the severity of aircraft response.

2 Introduction

The Air Force Research Laboratory is interested in improving the forecast of high altitude turbulence. The Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA) and National Center for Atmospheric Research (NCAR) have been studying turbulence forecasting at commercial altitudes for many years, and have systems in place to evaluate the effectiveness of the forecasts. These techniques are improving pilots' ability to avoid turbulence.[1] At present, NOAA's National Weather Service Aviation Weather Center, Aviation Digital Data Service web site includes forecast information from 20,000 ft to 45,000 ft. Due to its high cruising altitude, the U-2 must fly without the benefit of the guidance available on the NOAA site. There is also an increasing use of unmanned aerial vehicles such as the Global Hawk and Predator B, which might not be as successful in avoiding damage caused by turbulence as piloted aircraft.

High altitude turbulence that is not directly associated with close proximity to a jet stream is generated by gravity waves. Flow over mountains, storms, and jet streams can create local turbulence and, when this disturbed air is forced to deviate in a direction with a vertical component in a stable background field, gravity (or buoyancy) waves are created. As the waves propagate upward into lower density air, their amplitude increases in magnitude. Waves can reach critical levels where they reflect or break into turbulence, or when conditions are right they can simply grow in magnitude to the point where they become unstable. Both the mach surf and mechanical types of turbulence experienced by U-2 pilots can be attributed to the various stages of Clear Air Turbulence (CAT) (waves and breakdown).

CAT is the effect of an atmospheric condition on an airframe; therefore the response of the aircraft depends on the aircraft configuration, autopilot, and other factors beyond what is happening in the atmosphere itself. The primary motivation behind this work is to bridge the divide between atmospheric conditions and aircraft response. Traditional methods of studying aircraft turbulence usually consider the change in angle of attack caused by vertical gusts. This change in α causes an increase in the total lift produced, and the excess lift results in increased loading. Pilots report that periodic changes in air temperature can cause an autopilot attempting to maintain constant Mach number or constant indicated airspeed to respond as if the there were changes in air speed. In reality, no single atmospheric parameter changes all by itself. In a gravity wave, horizontal and vertical wind velocity and air temperature are all changing. Rather than speculate as to what is actually causing the hazardous conditions for the aircraft, it was decided that modeling and simulation science should be applied to these atmospheric problems.

We hope to understand the effects of CAT on aircraft in order to validate models of atmospheric turbulence. Thus a simulation has been built that models both the aircraft and turbulent atmosphere. This initial investigation will consider only the longitudinal (in-plane) dynamics. A separate wind reference frame must be used to properly handle wind disturbances. One interesting result of this report will be the comparison of traditional turbulence severity predictors with simulation runs using wave disturbances.

3 U-2 Simulation

A simulation of the U-2 aircraft was developed using the standard point mass three degrees of freedom equations of motion. The formulation of these differential equations is well documented by Stevens [2]. A fourth-order Runge-Kutta numerical integration method is used to propagate the states. The forces and moment are the drivers of the differential equations; they are computed using the stability derivative method. In this method, the forces and moment are calculated using a first order expansion, in which each state variable makes a contribution to the total force proportional to the stability derivative. This simulation formulation is identical to the one utilized for an Egrett aircraft investigation, given at the 2006 AIAA conference [3].

Discussions with the Lockheed Martin Aeronautics Company yielded access to stability derivatives and the autopilot mathematical definition [4, 5]. The autopilot uses aircraft state information to calculate the required elevator deflection necessary to return to a trim mach number.

The atmospheric environment also had to be simulated. The altitude profiles of atmospheric parameters such as temperature and density were modeled using the 1976 US Standard Atmosphere model[6]. Additionally, special attention had to be paid to reference frames with respect to wind speeds. This is because wind speeds are typically specified relative to the Earth reference frame, while forces are calculated in the aircraft body frame. Several reference frame transformations were used to ensure proper velocity comparisons were made.

Disturbances during the simulation come in the form of perturbed temperatures and wind velocities (both horizontal and vertical). Horizontal and vertical wind disturbances, U_w and

W_w are denoted by the subscript w, while background steady wind is denoted by U_f. Wind disturbances can be generated from a variety of sources: directed (such as steps or ramps in one of the disturbance variables), solutions to the gravity wave problem, numerical models of the atmosphere, and recorded data from aircraft.

All parts of the simulation, including equations of motion, autopilot, environmental conditions, and disturbances, were implemented in Matlab's Simulink® environment[7]. A trim point was found for steady, unaccelerated flight at cruise altitude. The state variables for this trim point are shown in Table 1.

Table 1: U-2 trim point for level unaccelerated flight

Altitude	Body Forward Speed	Body Vertical Speed	Mach	Thrust	Elevator Deflection
65000 ft	690 ft/s	0.5 ft/s	0.715	1790 lbs	0.02 rad

4 Traditional Gust Sensitivity

Classical turbulence sensitivity investigations utilize the gust sensitivity formula to predict maximum load factors based on vertical wind gusts with a $1 - cos$ shape. The concept is that an upward gust W_w will increase the angle of attack by $\tan^{-1}(W_w/U) \approx W_w/U$, which results in increased lift. The equation for the predicted maximum load factor, n, is then the increased lift divided by the weight of the aircraft, with an additional term to account for the gradual onset of the gust. This methodology is discussed in the Federal Aviation Regulations Part 23 Section 341 [8], as a possible demonstration of air-worthiness with respect to gusts.

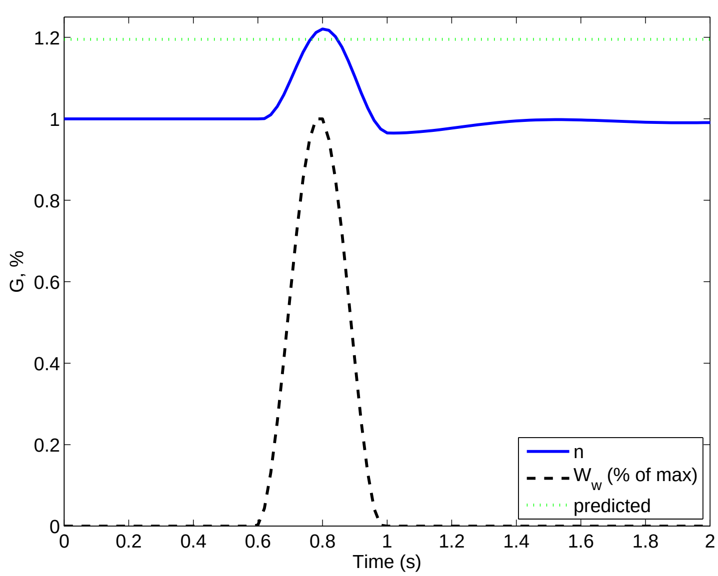

Figure 1: Response of U-2 to $1 - cos$ shaped vertical gust of magnitude 15 ft/s

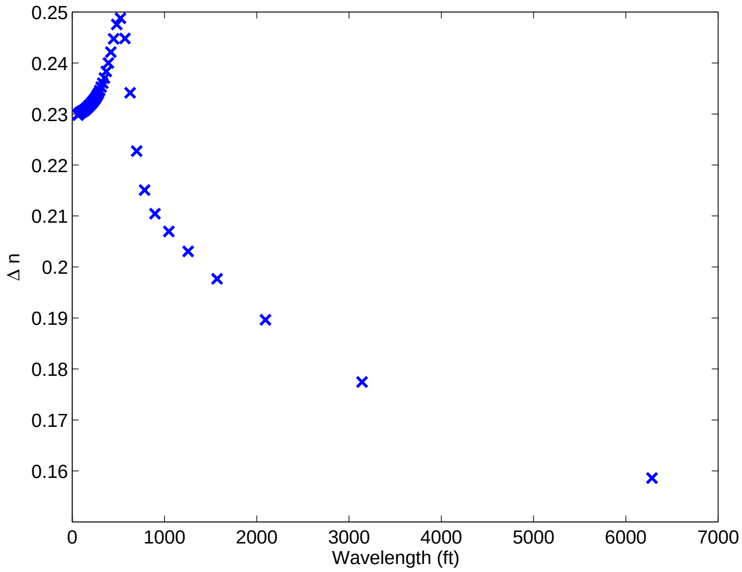

Figure 2: Difference between maximum and minimum steady state load factors when subjected to various wavelength continuous sinusoidal vertical gusts of magnitude 15 ft/s

After performing the calculation according to the above discussion, it was predicted that the U-2 would have a maximum load factor of about 1.2 after being subjected to a $1 - cos$ shaped vertical gust with magnitude 15 ft/s. This case was also run through the simulation, and the results are shown in Figure 1. Notice that the value from the gust sensitivity formula does a fairly good job of predicting the maximum load factor. It has been noticed from trials with other aircraft, however, that the gust sensitivity formula typically slightly under-predicts the maximum load factor, as is also seen in this case.

To better understand the limits of validity of the gust sensitivity formula, and also to steer the turbulence investigation in the direction of waves, simulations of aircraft flight through continuous sinusoidal vertical gusts were performed. Instead of stopping after a single $1 - cos$ shaped gust, the gust shape was repeated throughout the aircraft flight until a steady state condition was achieved. To maintain commonality, the disturbance magnitude remained 15 ft/s. A full spectrum of disturbance frequencies were considered. In each case, after a steady state condition was reached, the difference between the maximum and minimum load factors was recorded, Δn. This change in load factor was plotted against each trial disturbance wavelength in Figure 2.

The first feature to notice is the maximum Δn, which is close to 0.25. This is similar to the single gust case, which, as was shown in Figure 1, had a Δn of about 0.2. The second notable feature is the single prominent peak at a wavelength of about 520 ft. This suggests the excitation of a natural system mode. To validate this result, the U-2 aircraft system modes were approximated using a small perturbation method. The results of this analysis found the linear system modes at wavelengths of 700 ft and 8000 ft, the first of which matches

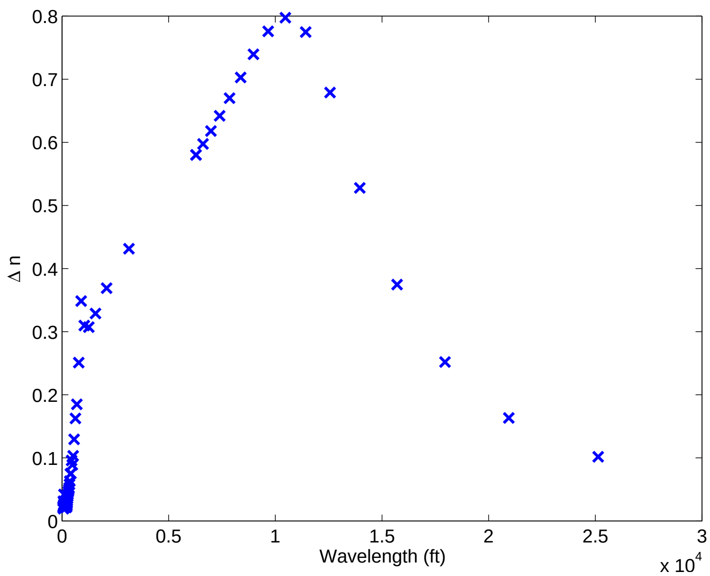

Figure 3: Difference between maximum and minimum steady state load factors when subjected to various wavelength continuous sinusoidal horizontal gusts of magnitude 5 ft/s

very well with the resonant peak in Figure 2.

The continuous vertical gust wave yielded an interesting look at traditional gust sensitivity theory, and is more analogous to the 'mechanical' turbulence experienced by pilots. Another test case is to consider a continuous horizontal gust wave. This will resemble the 'mach surf' type of turbulence that is more interesting for the U-2 altitudes. In this case, some analysis was done to equate the load factor disturbance magnitude for the single gust case for both the vertical and horizontal gusts. Thus, opposed to a gust magnitude of 15 ft/s for the vertical wave, the horizontal wave had a magnitude of 5 ft/s.

There was some concern over why the U-2 would be more susceptible to horizontal gusts rather than vertical gusts, which are the typical target of turbulence studies. Discussions with the U-2 program office yielded the answer. Due to the high operating altitudes, the U-2 flies within a tight window bounded by the stall and mach limits. The autopilot must be very aggressive to ensure maintenance of this window. Thus disturbances that excite the autopilot, such as horizontal gusts and changes in temperature, cause more dramatic aircraft responses than those which have little effect on aircraft speed, such as vertical gusts.

A simulation similar to that above was performed for the horizontal continuous wave gust. The results of the simulation are shown in Figure 3. The first notable feature of the graph is the structure of the curve: there are two prominent peaks. The low wavelength peak is a recurrence from the previous simulation. An additional peak, close to the second system mode of 8000 ft, is also apparent. The appearance of the second mode only in the horizontal case suggests that the mode is associated with the autopilot of the aircraft, while the first is associated with the aircraft itself. Thus only those disturbances that directly affect the aircraft's speed will excite the second mode.

The second feature to note is the magnitude of the peaks. The first peak has a magnitude similar to that of the vertical case. The system mode associated with the airframe has limited magnification potential. However the second peak shows that the aggressive autopilot has magnified the disturbance dramatically, and produced some large swings in the load factor. Clearly, for some disturbance frequencies, this continuous horizontal wave produces much larger effects than was predicted by the gust sensitivity formula.

A separate series of simulation trials were performed using temperature as the disturbance. When scaled appropriately to a magnitude of about 6 K, this effective change in mach number creates an output very similar to what is seen in Figure 3.

5 Simple Gravity Wave Theory

Long's equation describes mountain waves that are stationary relative to the ground (not time-varying). The formula is

$$\partial^2\delta/\partial X^2 + \partial^2\delta/\partial Z^2 + \left(N^2/U^2\right)\delta = 0, \tag{1}$$

where $\delta(X, Z)$ is the vertical displacement of a streamline from its undisturbed height [9]. The simplest solution is

$$\delta(X, Z) = a\sin(kX + mZ) \tag{2}$$

such that

$$m^2 = N^2/U_f^2 - k^2, \tag{3}$$

where k and m are the horizontal and vertical wave numbers, and N is the Brunt-Väisälä frequency, the natural frequency of a vertically oscillating air mass. The horizontal velocity is then

$$\begin{aligned} U_w &= U_f(1 - \partial\delta/\partial Z) \\ U_w &= U_f\left(1 - am\cos(kX + mZ)\right). \end{aligned} \tag{4}$$

The vertical velocity of the wind is

$$\begin{aligned} W_w &= U_f\partial\delta/\partial X \\ W_w &= U_f ak\cos(kX + mZ). \end{aligned} \tag{5}$$

The wave also affects temperature. A rising parcel of air decreases in temperature as it expands adiabatically. Using the isentropic relationship, a solution can be found for $\phi = \ln\Theta$, where Θ is the potential temperature, or the temperature an air parcel would have if adiabatically compressed to a reference pressure.

$$\phi = \phi_o + B\left(Z - a\sin(kx + mz)\right) \tag{6}$$

describes the effect of the linear wave field, where B is the background stability, $d\phi/dZ$, and ϕ_o is the constant reference value.

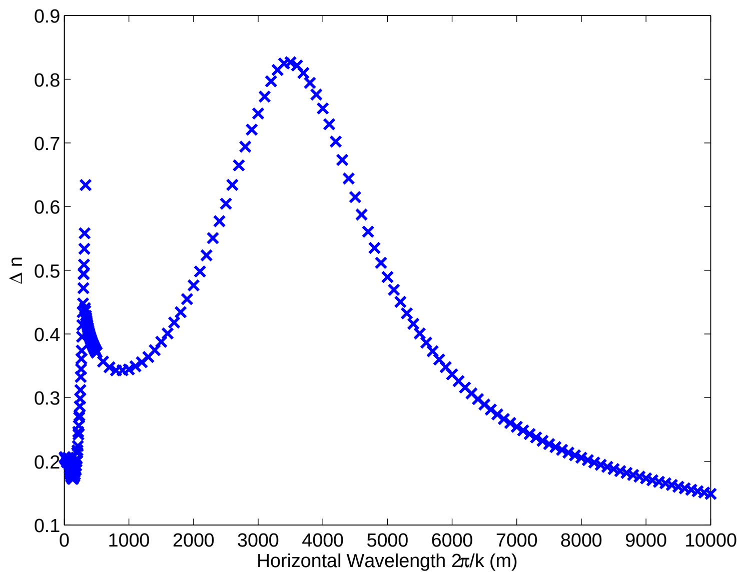

Figure 4: Difference between maximum and minimum steady state load factors when subjected to various wavelength simulated gravity waves with magnitude $U_w = 5$ ft/s, $W_w = 15$ ft/s

The result of implementing equations (4), (5), and (6) is a wave with wind disturbances 180° out of phase with each other and the temperature disturbance 90° out of phase with the wind.

This simulated gravity wave was used as a disturbance in the U-2 simulation. The magnitudes of vertical and horizontal wind velocities, along with temperature disturbances, were scaled appropriately to compare to the previous simulation runs. Once again, the steady state maximum change in load factor was plotted against a spectrum of wavelengths, chosen here as $2\pi/k$, in Figure 4. This graph has a very similar structure to that from the horizontal wave case in Figure 3. There are two peaks, close to the system modes of 700 and 8000 ft. Also, note the magnitudes of Δn are larger in this case due to the combination of all three disturbances (horizontal and vertical wind and temperature). The increase in magnitude is not as large as might have been expected, however, because the disturbances are out of phase.

6 Atmospheric Simulation Results

A mesoscale weather forecasting model was used as the source of another disturbance type for the simulation. This model was modified to automatically and dynamically resolve grid spacing to increase the resolution in regions with higher vorticity [10]. A two-dimensional representation of the 11 January 1972 Boulder windstorm was generated, and one ray of the data was chosen as the simulation's path. These disturbances, which are relatively large and slow, are shown in Figure 5.

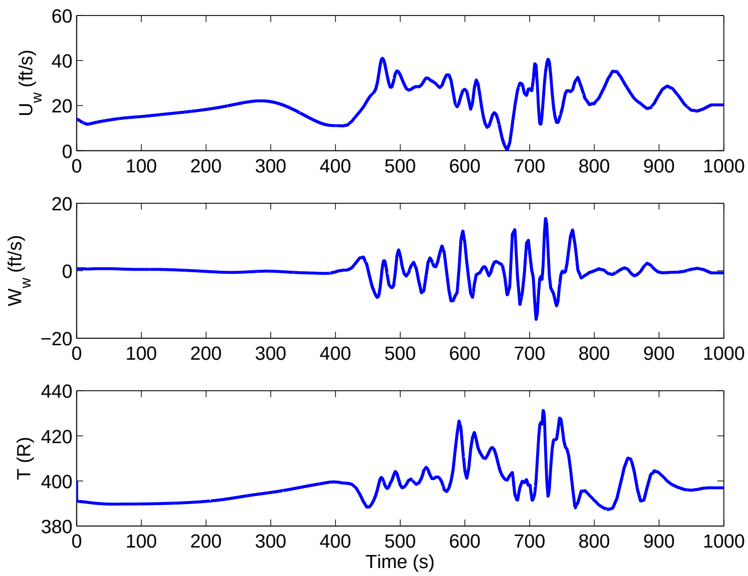

Figure 5: Ray of data used as simulation disturbance taken from mesoscale model of 1972 Boulder windstorm

The simulation output load factor is shown in Figure 6. Due to the large changes in horizontal winds and temperature, the load factor excursions are quite dramatic. To compare

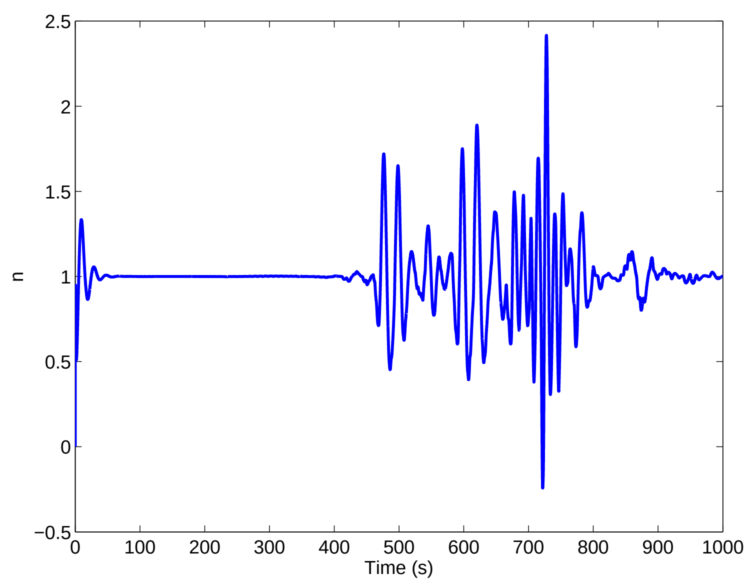

Figure 6: Simulation output of aircraft load factor when subjected to disturbance shown in Figure 5

with previous simulations, the Δn for this case is 2.65, much larger than any seen previously.

7 Conclusion

Due to its aggressive autopilot, the U-2 is highly susceptible to 'mach surf' type turbulence: changes in mach through horizontal wind gusts or changes in temperature. Gravity waves, especially those of specific frequencies, are particularly disruptive, as they change wind velocities and temperature at the same time and can be magnified by aircraft system modes. Load factors resulting from these disturbances exceed by a large margin those predicted by traditional gust sensitivity theory using single vertical gusts. Clearly, development of forecasting capability of these turbulent events should be a priority considering the push toward high altitude reconnaissance in the military.

Efforts are underway to extend this study. Specifically, an additional atmospheric model is being considered: a very high resolution 3D direct numerical simulation[11]. This atmospheric model considers the breakup of a shear flow in a stratified flow. Statistics will be gathered using a variety of simulation runs from a variety of paths through the flow and times in the flow's evolution.

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List of Acronyms and Symbols

CAT Clear Air Turbulence

a Gravity wave amplitude

k Horizontal wave number of gravity wave

m Vertical wave number of gravity wave

N Brunt-Väisälä frequency

n Load factor

U Aircraft body-relative forward speed

U_f Horizontal steady background wind velocity

U_w Horizontal wind disturbance velocity

W_w Vertical wind disturbance velocity

X Aircraft horizontal position

Z Aircraft vertical position

α Angle of attack

Θ Potential temperature