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Estimation of Flight Load History Using Global Positioning System Data

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Introduction

THE Swedish jet trainer Saab 105 with Swedish Air Force designation SK60 has been in military service since the late 1960s and is today used for military pilot training. The need for monitoring the aircraft structural condition increases with increasing flight hours. Consequently, to instrument an old aircraft such as the SK60 with flight load recording devices can be expensive and invoke complicated procedures including new airworthiness tests. Here a cost effective method is used to estimate the flight load history of the aircraft using a global positioning system (GPS) receiver only.

The aircraft fatigue environment is mainly dependent on the normal accelerations of the aircraft, and hence, the load factor n_z is a suitable parameter for modeling this kind of problem. To obtain an overall view of the aircraft fatigue life, a load factor history can be performed counting the number of occurrences a certain load factor level is reached or exceeded for a given time interval. A large number of flights containing aircraft load factor data recorded by an accelerometer is normally divided into different flight missions or segments such as ascent, cruise, loiter, descent, etc. A load factor history is then calculated for the different segments to obtain the total number of load factor occurrences.[1] With use of this load factor history, the fatigue load environment of the aircraft can be predicted, but this part is excluded in this study.

The different SK60 used in the daily training are randomly distributed to the pilots before flight. Because the individual aircraft are changed from flight to flight, the pilots do not get used to the different aircraft characteristics and behavior. This also means that the different individual aircraft are exposed to similar loads over long time ranges.

The approach in this study is to use a fully instrumented reference SK60 measuring normal accelerations of the aircraft's center of gravity, which is directly related to the load factor n_z. To get an overall view of the load factor history of all of the other SK60 in the training squadron, it is proposed to instrument all of them with a GPS receiver and to use the reference aircraft for complementary information. The reference aircraft used in this study is the fully instrumented SK60:072 located at the Swedish Defence Materiel Administration (FMV) in Linköping, Sweden.

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Load Factor History

Measuring the normal acceleration of the aircraft's center of gravity leads to the load factor n_z, which is given in units of gravitational acceleration, where $g = 9.81$ m/s^2, and the steady-state load factor is $n_z = 1.0\ g$. Load factor history tables or plots are usually separated into load factors greater than $1.0\ g$ and load factors less than $1.0\ g$. A load factor exceedance is obtained if a certain load factor level is met or exceeded, that is, $n_z + \Delta n_z$, or $n_z - \Delta n_z$ during the time the load factor departs from the reference level $1.0\ g$ to the time the load factor returns to $1.0\ g$. During this time, the load factor exceedance for a specific load factor level is only counted once and then is called an occurrence. Furthermore, a FORTRAN program has been developed in this study to perform the load factor occurrence calculations.

The load factor is often separated into two parts, maneuver load factors and load factors due to gusts. The maneuver load factors are typically of a lower frequency than the load factors caused by gusts. The load factors due to gusts are often estimated using a power spectral density method using an empirical model of the atmospheric turbulence together with the dynamics of the aircraft.[2]

Reference Aircraft

The operational SK60 of the Swedish Air Force are not equipped with any aircraft flight data recording system at all. The SK60:072 is stationed at FMV in Linköping and is specially instrumented with various devices for data recording during flight. The SK60:072 is equipped with an inertial measurement unit (IMU) that measures the accelerations and angular rates of the aircraft. The GPS receiver in the SK60:072 can provide positioning data at a frequency of 2 Hz. The IMU can provide the acceleration in the aircraft body normal direction at a frequency of 60 Hz. The GPS positioning data and the normal acceleration data from the IMU are used as reference data in this work. The number of flights made available for this study is strictly limited. Normal acceleration and GPS data for nine flights are used, but only three of them contain 2-Hz GPS data. The remaining six flights contain 1-Hz GPS data, which is too poor to model the maneuver load factors accurately, but the IMU data are still used from these flights.

Calculating the Maneuver Load Factors from GPS Data

A GPS receiver is a very powerful and widely used device for position and velocity determination of an aircraft.[3] In this study, the 2-Hz GPS positioning and velocity data are used to estimate the flight path in terms of a B-spline curve following the GPS records. In a previous study, a method involving a constrained least-squares approach to find a B-spline curve representing a smooth flight path suitable for flight visualization is successfully performed.[4] Because this method of estimating the load factor history needs to be performed for all of the flights, a fast method is desirable. Consequently, a less computationally intense interpolation approach is adopted here.

When a suitable knot vector is chosen, the linear system of equations for solving the B-spline coefficients can be formulated for the GPS velocity V_{GPS} as

$$\sum_{j=1}^{n} a_j N_{j,k}(t_i) = V_{\mathrm{GPS}}(t_i), \qquad i = 1, 2, \ldots, n \tag{1}$$

where n is the number of GPS velocity records and the $N_{j,k}(t_i)$ are the basis functions of order $k = 4$ calculated at the time instants t_i. The n unknown coefficients a_j are obtained by solving Eq. (1) using FORTRAN subroutines where the sparse banded structure is taken into account.[5] Similar calculations are performed to obtain smooth curves to represent the flight path angle γ_{GPS}, heading ψ_{GPS} and altitude h_{GPS}.

One advantage of using a curve fit to the GPS data for modeling the flight path is that the first derivative with respect to time can easily be calculated for any desired time instant of the flight path. Consequently, the flight path is estimated independently of an aircraft model.

To be able to model the load factor, the equations of motion of the aircraft need to be defined. Optimal aircraft trajectories representing the SK60 with a performance model are computed by Ringertz and successfully flight tested by the Swedish Air Force showing good agreement.[6] Such a performance model is used here to represent the aircraft. As also outlined by Ringertz[7] the equations of motion for such a performance model can be expressed as

$$m\dot{V}_{\mathrm{GPS}} = T\cos(\alpha+\epsilon) - D - mg\sin\gamma_{\mathrm{GPS}} \tag{2}$$

$$mV\dot{\gamma}_{\mathrm{GPS}} = T\sin(\alpha+\epsilon)\cos\phi + L\cos\phi - mg\cos\gamma_{\mathrm{GPS}} \tag{3}$$

$$mV_{\mathrm{GPS}}\dot{\psi}_{\mathrm{GPS}}\cos\gamma_{\mathrm{GPS}} = T\sin(\alpha+\epsilon)\sin\phi + L\sin\phi \tag{4}$$

where m is the mass of the aircraft, T thrust, α angle of attack, L lift, and D drag. Furthermore, ϵ is the angle of engine thrust relative to the body-fixed coordinate system. The heading represented by ψ_{GPS} is defined as zero in the east direction and positive counterclockwise. Finally, the bank angle ϕ is defined as the the angle of roll displacement around the velocity vector with wings level defining $\phi = 0$.

When International Standard Atmosphere conditions are assumed and engine and aerodynamic data are tabulated, the thrust T, lift L, and drag D can be calculated using the GPS data. The aerodynamic data are obtained from wind-tunnel tests and validated in flight tests at Saab and FMV.

The mass of the aircraft is assumed to be assembled by the empty mass, pilot, copilot, and 90% of maximum fuel leaving 10% for taxiing and takeoff, with decreasing fuel mass through out the flight calculated from the engine data. The equations of motion (2–4) are then solved using Newton's method for the unknowns α, ϕ, and the thrust control setting δ_T for any desired time instant of the flight path.

When the total mass m of the aircraft is used together with the lift L from the calculations involving Eqs. (2–4), the load factor can be expressed as

$$n_z^{\mathrm{GPS}} = L/mg \tag{5}$$

Finally, it is evident that solving Eqs. (2–4) together with Eq. (5) not only introduces the n_z^{GPS}. Estimates α, ϕ, and δ_T are also obtained for the flight using the methodology outlined.

Superimposing Higher Frequency Load Spectra

When flying through turbulent air or gusts, the aircraft is exposed to accelerations, which influences the fatigue life of the aircraft. The frequency content of the load factor n_z^{GPS} calculated from the GPS data is not sufficiently high to resolve the load factors occurring from gusts. From the 60-Hz IMU data, it is noticed that the load factors due to gusts are strongly dependent on the altitude of the aircraft. The lower the altitude is, the higher amplitude of the measured accelerations. This is probably due to turbulent air caused by the interaction between local wind condition and the ground.

The gust is often treated as a random process, and this approach is also adopted here.[8] The six flights containing 1-Hz GPS data and 60-Hz IMU data are used to model the influence of gusts on the load factor.

According to the Nyquist criterion, the 2-Hz sampled GPS data used to calculate the n_z^{GPS} results in load factor occurrences counted at a maximum frequency of half the sampling frequency, that is, 1 Hz (Ref. 9). Load factor occurrences with higher frequencies than 1 Hz are assumed to occur from gusts and are then randomly superimposed on the n_z^{GPS}. If GPS data at a higher sampling frequency are available, it can be further verified if the maneuver load factors are accurately resolved because the load factor occurrences can be counted at higher frequencies.

The IMU load factor data from the six flights need to be filtered to contain only frequencies greater than 1 Hz. This is obtained by performing discrete fourier transform (DFT) on the 60-Hz IMU normal acceleration data. The DFT coefficients N_z^{IMU} are calculated according to

$$N_{z,l}^{\mathrm{IMU}} = \frac{1}{M}\sum_{k=1}^{M} n_{z,k}^{\mathrm{IMU}} \exp\left[-\frac{i2\pi(k-1)(l-1)}{M}\right] \qquad l = 1, 2, \ldots, M \tag{6}$$

where M is the total number data points. The filtering is performed by setting the appropriate $N_{z,l}^{\mathrm{IMU}}$ corresponding to frequencies less than 1 Hz to zero. The filtered $\hat{n}_z^{\mathrm{IMU}}$ is obtained using the inverse DFT based on the new DFT coefficients as

$$\hat{n}_{z,k}^{\mathrm{IMU}} = \sum_{l=1}^{M} N_{z,l}^{\mathrm{IMU}} \exp\left[\frac{i2\pi(l-1)(k-1)}{M}\right] \qquad k = 1, 2, \ldots, M \tag{7}$$

Once the DFT is performed the filtered $\hat{n}_z^{\mathrm{IMU}}$ is separated into four parts defined by the altitude ranges

$$\begin{aligned} 0 &< h_{\mathrm{GPS}} \le 500\ \mathrm{m} \\ 500 &< h_{\mathrm{GPS}} \le 1000\ \mathrm{m} \\ 1000 &< h_{\mathrm{GPS}} \le 1500\ \mathrm{m} \\ 1500 &< h_{\mathrm{GPS}} \qquad\ \mathrm{m} \end{aligned} \tag{8}$$

The filtered $\hat{n}_z^{\mathrm{IMU}}$ from the four altitude segments are then randomly superimposed on the n_z^{GPS} to obtain the final load factor n_z for an arbitrary time instant of the flight.

Numerical Example

The methodology outlined can now be examined and validated. The total flight time for the three flights with 2-Hz GPS data is limited to only 1.5 h. To verify fully the method outlined in this report, substantially longer total flight time, containing flights in different weather and flight conditions, are needed. However, still some interesting results can be realized using only these three flights.

Unfortunately, the three flights contain 15-Hz IMU data only. To make an accurate comparison between the load factor from the GPS with superimposed higher frequency IMU data and only the measured IMU data, the 60-Hz IMU data used in the DFT are also filtered to match the 15-Hz IMU data. First, the number of load factor occurrences of the three flights are calculated using only the GPS data without superimposing the higher frequency IMU data. The number of occurrences for the load factors greater and less than 1.0 g, respectively, are shown in Fig. 1, where $\Delta n_z = 0.25\ g$. The number of load factor occurrences from the 15-Hz IMU data recorded from the same flights as the GPS records is also visualized in Fig. 1 and are marked with squares. It is evident that the number of occurrences for $n_z = 1.25\ g$ and $n_z = 0.75\ g$ using only the GPS data is much lower than the number of occurrences from the 15-Hz IMU data. The number of occurrences from the GPS data in this study are assumed to correspond to the maneuver load factors. Consequently, load factors due to gusts are not resolved here.

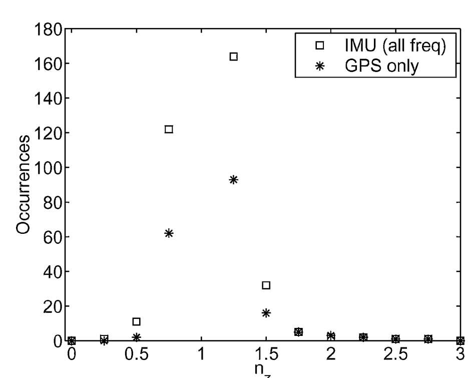

Fig. 1 Load factor occurrences excluding superimposed IMU data.

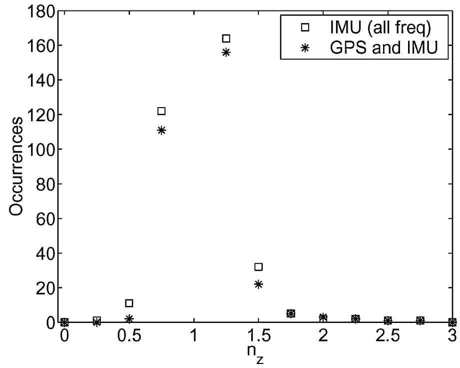

Fig. 2 Load factor occurrences including superimposed IMU data.

To make an estimate of the load factors occurring from gusts, the filtered and randomly chosen $\hat{n}_z^{\mathrm{IMU}}$ from the four altitude segments are superimposed on the calculated n_z^{GPS} before the load factor occurrence program is used. Figure 2 shows the number of load factor occurrences calculated when the $\hat{n}_z^{\mathrm{IMU}}$ is superimposed on n_z^{GPS}. Note that the number of occurrences increases especially for the load factors $n_z = 1.25\ g$ and $n_z = 0.75\ g$, which is due to the superimposed $\hat{n}_z^{\mathrm{IMU}}$ on the GPS maneuver load factor. To resolve the load factor occurrences accurately, the frequency of the IMU data needs to be higher than 15 Hz, preferably even higher than 60 Hz. Nevertheless, a conclusion to be drawn based on Fig. 2 is that the number of occurrences for the GPS data with superimposed reference IMU data agrees rather well with the number of occurrences obtained from just the IMU data.

Summary

To keep the aircraft instrumentation cost down, a method for estimating the load factor history of the SK60 using a GPS receiver and IMU normal acceleration data from a reference aircraft is proposed to keep track of the aircraft usage.

The method of superimposing filtered IMU data from a reference aircraft shows promising results even though the number of flight hours available for this study is limited. The number of occurrences using GPS data with superimposed higher frequency IMU data agrees rather well with the number of occurrences obtained using only the IMU data. It can also be concluded that if the SK60:072 is used in daily training, a larger set of data can be recorded from the IMU. The IMU data can possibly be used to model higher frequency accelerations caused by gusts more accurately by dividing the different flights into not only altitude segments but also into, for example, different weather and aircraft velocity conditions.

The maneuver load factors in this study are assumed to be resolved using 2-Hz GPS data. This can be further improved if a GPS receiver with higher data output rate is used.

Furthermore, the DFT filtering calculations of the higher frequency IMU data are computationally expensive, but in turn, it only needs to be performed once. The calculations using the GPS data assembled with the equations of motion to obtain the load factors and the corresponding occurrences are performed in a few seconds for 1 h of flight.

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Comparisons of a Gurney and Jet Flap for Hingeless Control

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Introduction

ADVANCES in fluidic control have recently raised the proposition of hingeless flow control. For purposes of stealth, reduced vehicle weight, increased robustness, and damage tolerance as well as compactness, the hingeless methodology is extremely attractive. Implementation methods are driven by available fluidic control technology exemplified of late by the synthetic jet actuator (SJA).[1–3] Flow control or manipulation may be achieved through active or passive means; for moment and force augmentation active methods are more feasible. Continuous or oscillatory blowing may be used to suppress separation,[3] "virtually alter the surface,"[4] or cause supercirculation through circulation control effected via trailing-edge and Coanda surface blowing.[5–7] Although it has been demonstrated that control of flow separation can be used for pitch control at high angles of attack,[2] this mechanism is not available or viable at low angles of attack, where aerodynamic efficiency would be marred by large-scale flow separation. At low incidence, the most receptive and effective location for modification to generate pitching moment is the trailing edge. Obvious modifications are the flap. Moments are generated through flap deflection by movement of the rear stagnation point yielding increased vertical momentum transfer. Other trailing-edge modifications are pneumatic; either a jet flap, where a high-velocity jet is issued from the trailing edge at an inclination angle, or a blown flap, where the jet is directed over the flap. All these methods are effective but may require significant quantities of air for operation.

The Gurney flap[8,9] has been shown to be a highly effective small-scale (typically 0.5–1.5% of the chord) modification that can achieve significant lift and pitching moment generation. The flap functions by essentially increasing the downward deflection of the trailing-edge flow, facilitated through the formation of a series of counter-rotating vortices similar to that of a von Kármán vortex street. A

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