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Modal Parameters of Light Aircraft Wing

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Summary: The main aim of this work is to extract modal parameters of a light aircraft wing. Modal parameters like modal frequency, modal damping and mode shapes characterise the dynamic response of a particular structure and can be used for determining an excess wing flexure as well as the long-term effect of fatigue.

For the experimental part the response of the Piper Warrior II was recorded during ground runs. A set of temporarily attached accelerometers was used to record the response of the wing and the signals were recorded. Subsequently a Frequency Response Function was generated in the post-processing stage, which resulted in determining the first and second bending modes as well as the first twisting mode. A Finite Elements Model was applied to validate the results.

Due to the limitations of the taxiing speed the method cannot excite higher frequency modes, however the findings can find numerous applications in real time in-flight flexure monitoring.

Keywords: wing flexure, modal frequency, operational deflection shapes, frequency analysis, wing bending, wing twisting

Introduction

Vibration problems in structures and operating machinery often involve the excitation of structural resonance or modes of vibration. An example of a severe resonance-related problem during aircraft operation is flutter. Even though the initiation of flutter may be much more complex than resonance excitation, resonance is one of the contributions to structural failure when flutter occurs.

If a continuous monitoring of wing deflections is required, it is necessary to first obtain the natural frequencies of the structure. This research is based on investigating wing deflection behavior from a vibration analysis approach to extract modal parameters e.g. modeshapes, natural frequency and modal damping estimates.

In order to approach wing deflections from a vibration analysis perspective, a ground vibration test (GVT) was decided upon as a means to obtain information on resonant frequencies of an existing aircraft [1].

An analysis based on Operational Deflection Shapes (ODS) was conducted to acquire modal parameters of a Piper Warrior II. The aim of ODS measurement is to determine the forced dynamic deflection at the operating frequency to obtain a representation of the absolute deflection of a structure due to unknown but real forces [2]. The experimental procedure involved data acquisition from a reference pair of accelerometers mounted on the roof of the aircraft and a set of response accelerometers on one of the wings. The input excitation was operational forces induced by low-speed taxiing across asphalt and grass surfaces followed by short accelerated runs along the runway.

A Measurement Set method was used as only seven input channels could be measured for each run. Seven ten-minute measurements were required to obtain enough spatial resolution of the wing. A repeatability check was performed to verify that the unmeasured excitation was stationary between the measurement sets. Data analysis was performed using two different methods of Operational Deflection Shape Frequency Response Functions (ODS FRF) analysis.

Mode Identification for Output-only Measurement (ODS)

As a result of numerous constraints common in the aviation industry, the method of output-only modal analysis has been approached by applying a peak-picking technique to the Auto Power Spectrum (APS) and Cross Power Spectrum (CPS) of the measured responses, resulting in operational deflection shapes and approximate values for the resonance frequencies [3].

A new post-processing method of interest to this research associated with ODS FRF is detailed in [4]. By definition, it is required that all measured responses of the ODS have correct magnitudes and phases relative to one another. Out of the two proposed methods of measurements the Measurement Set method was applied. According to this method the data acquisition simultaneously acquires some of the responses, along with a reference response. An entire test then consists of acquiring two or more measurement sets.

When data is collected in measurement sets, the fixed reference point measured with each set preserves the relative phase among all responses in all measurement sets. If the phase of the reference is subtracted from the phase of each response in its measurement set, the response from all measurement sets will have the correct phase relationship [4].

In order for excitation levels to be considered stationary, the APS of the reference signal should not vary between successive measurements [3, 4]. If the peaks in two successive APSs are at the same frequencies when they are overlaid, it can be concluded that the modes (and hence the physical properties) of the structure are stationary.

The ODS FRF, a complex valued frequency domain function, is formed by combining the APS of a roving response with the phase of the CPS between the roving and reference response. It therefore contains the correct magnitude of response (the APS of the roving response) and correct phase relative to the reference response. However, in the case of non-stationary excitation, the magnitudes of a set of ODS FRFs must be corrected to account for these changes between measurement sets. This is achieved by multiplying the magnitude of each ODS FRF in a Measurement Set by a Scale Factor.

This Scale Factor corrects each of the ODS FRF magnitudes according to the average level of all of the reference response signals, which can be calculated for any desired range of frequency samples.

A conventional modal analysis would require large shakers to provide enough structural excitation to obtain modal parameters. However, as an operational aircraft was used, it was impossible to apply equipment that could cause unnecessary structural fatigue. As a result, an Operational Modal Analysis procedure was designed in an attempt to extract the required information with the range of resources available.

The GVT procedure involved a grid consisting of 32 measurement points on the upper surface of the wing and two reference points on the roof was created (Figure 1). The data acquisition system had only 7 input channels, therefore a set of 7 piezo-electrical accelerometers was used. The entire experiment was carried out in 7 measurement sets. Only the reference points were permanently occupied by two accelerometers while the remaining 5 accelerometers were repositioned for each measurement set.

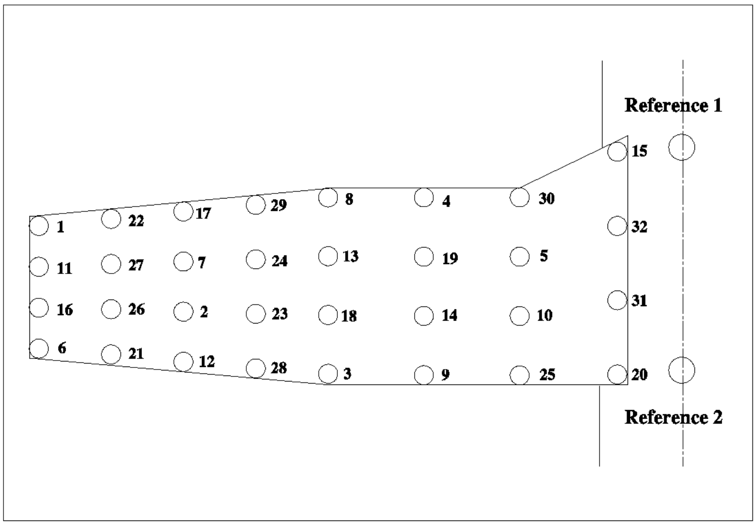

Fig. 1: Measurement points on the wing

Measurements sets involved data collected from 10-minute ground runs, each consisting of low speed (40 km/h approximately) and high speed (80-100 km/h) taxiing. The longer than usual time frame was necessary in order to compensate for the differences in conditions between ground runs.

There was no need for real time processing so the signals were stored on a laptop computer for post-processing. The data acquisition process can be described by Figure 2.

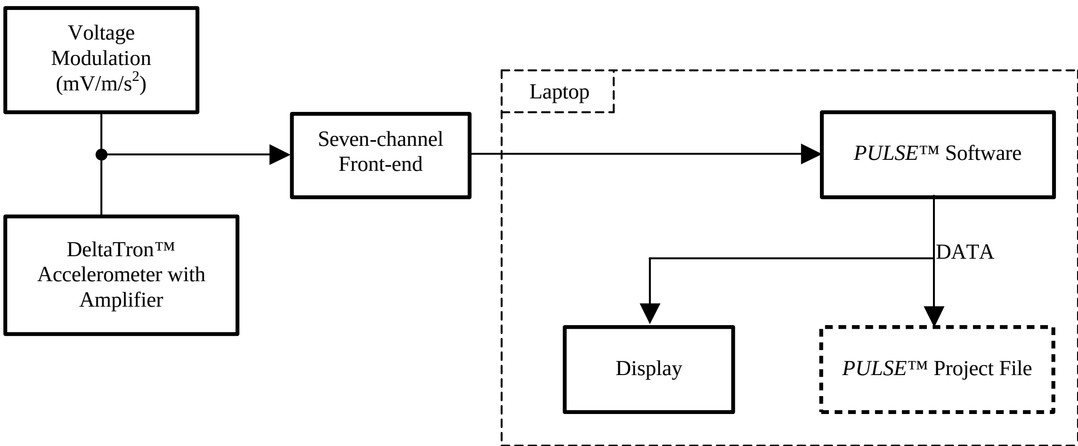

Fig. 2: Block diagram of data acquisition

PULSE™ is a Microsoft™ Windows NT™ based software platform that is used for sound and vibration measurements [5]. During one measurement data was captured as 10-minute time signals, with the accelerometer output in terms of voltage, in the laptop memory. An exponential window was used to minimise leakage.

ME'scopeVES utilises multi-channel time or frequency domain data acquired during machine operation, or the excitation/loading of a structure. It displays time-based or frequency-based ODSs, mode shapes and other functions directly from measured data.

The ODS FRF provides the true response (in displacement, velocity or acceleration units) for each roving sensor, together with a phase relative to the reference response. Therefore if data from a single reference set of ODS FRFs is applied to a model of the structure, the resulting ODSs are the true response at each roving accelerometer, with correct phases relative to all other roving responses.

Also, at or near a resonant frequency, the response is often dominated by the resonance, so the ODS is approximately the same as the mode shape corresponding to that resonance [6]. The aim of this analysis was to extract wing ODSs that appeared to be dominated by resonant frequencies. Two sets of ODS FRFs were generated, one for each reference point.

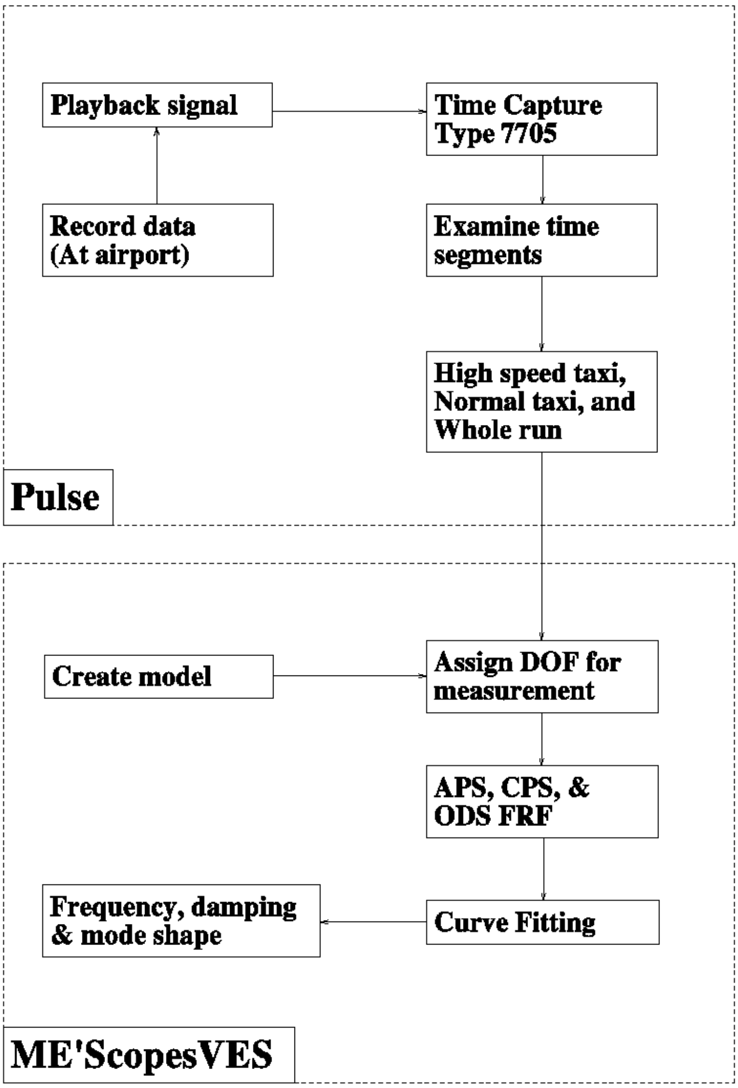

Fig. 3: Schematic of data analysis procedure

Figure 3 provides the chart of the post-processing procedure using the example of reference accelerometer 2 and roving accelerometer 4.

Before the data analysis started a repeatability of the measurement sets was tested. All measurement points exhibited a high level of repeatability despite being used on different runs (Figure 4).

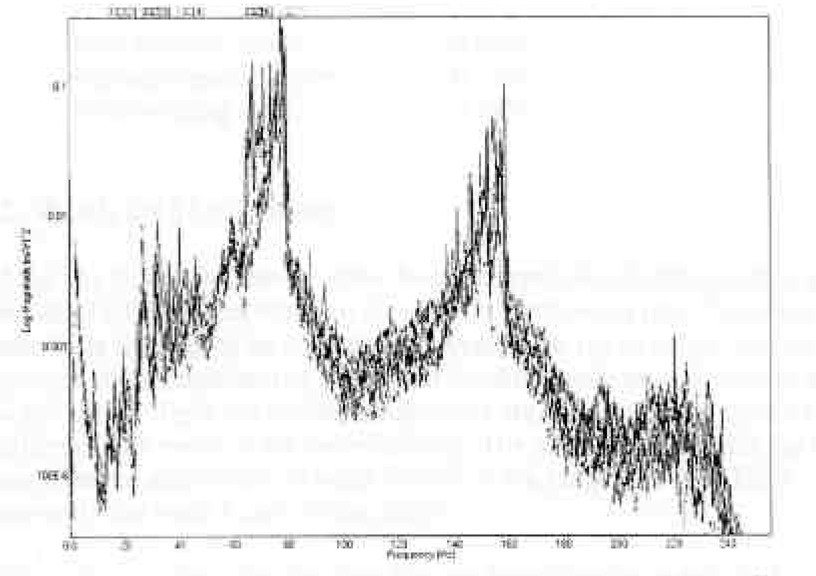

Fig. 4: Repeatability check

Results

Three types of analyses were performed: using the entire runs as the dataset, using only high speed parts of the runs and using only low speed parts of the runs. They were all subjected to two different curve-fitting methods and as a result there were six values for each mode and three values of damping for each mode (the Global Peak curve-fitting method does not provide damping). All values of modal frequencies were very close to each other while the values of damping varied significantly for different data sets. Based in this procedure it can be concluded that the natural frequencies for the Piper Warrior II wing are:

First bending mode	8.7 Hz,
Second bending mode	17.9 Hz,
First twisting mode	19.6 Hz.

while higher modes were not clearly identifiable.

With much less certainty, using the average values only, the values of modal damping were established to be:

First bending mode	5.43%,
Second bending mode	1.05%,
First twisting mode	0.73%.

Conclusions

This aim of this investigation was to analyse the wing deflection behavior of a light aircraft, from a vibration analysis approach. Modal parameters e.g. modeshapes, natural frequency and modal damping estimates could then be made. The conventional procedure to prove flutter airworthiness requires an initial computer analysis, followed by wind tunnel tests, ground vibration tests (GVT) and flight flutter tests.

A GVT was selected as a means of obtaining information on resonant frequencies of an existing aircraft. A GVT is a necessary step toward a simplified flutter analysis as it provides the modal parameters (natural frequency, modal damping, and mode shape) and structural damping required for the flutter analysis of an aircraft. The focus was on the vibration analysis aspect of GVT, rather than prediction of a critical flutter speed.

In order to define the modes of vibration of the aircraft wing, an operational deflection analysis procedure was developed, as the equipment for standard vibration excitation was not accessible due to various constraints. This analysis method is used when operating forces are difficult to measure. Reference signals from accelerometers representing input excitation were required, so that the response signals from accelerometers representing the resulting deflections can be compared. This procedure provides unscaled modeshapes of the structure being tested.

A GVT was conducted on a Piper Warrior II aircraft. The experimental procedure involved data acquisition from a pair of accelerometers mounted on the roof of the aircraft and a set on one of the wings. The input excitation was operational forces induced by high and low-speed taxiing across asphalt and grass surfaces. A Measurement Set method was used as only seven input channels could be measured for each run. Four ten-minute measurement runs were required to obtain enough spatial resolution of the wing.

The time signals obtained were used to generate Operational Deflection Shape Frequency Response Functions (ODS FRF). These functions were curve fitted to obtain mathematical descriptions of resonance curves representing natural frequency. The data acquired could only be used to estimate with confidence the lower modal values as the peaks in the ODS FRF were not sufficiently pronounced at frequencies higher than 30 Hz.

A repeatability test conducted by overlaying Auto Power Spectra of the reference signals for all measurement sets verified that the excitation forces were stationary between the measurement sets. Estimates of the first two bending modes, as well as the first twisting mode, were successfully extracted from the two analysis methods carried out. This was obtained from the deflection shape that represented the modes most closely.

This research can be expanded by using the GVT data to predict a critical flutter speed from aeroelasticity theory. The same approach can be used for the purposes of structural health monitoring by comparing the values of modal frequencies and damping over longer periods of operation.

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