CAPTIVE CARRY TESTING AS A MEANS FOR RAPID EVALUATION OF UAV HANDLING QUALITIES

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Abstract

A preliminary evaluation has been made of a captive carry rig for testing handling qualities of small UAVs. The method used was to attach the vehicle such that it is free to rotate on a tripod above a car. Results indicate that the method is very suitable for evaluating aircraft trim and control surface effectiveness. The method is shown to provide repeatable, sufficiently accurate data to provide information regarding to aircraft stability and control at a preliminary design stage and at low cost. Further work is required to ascertain the ability to measure forces and moments such that derivatives can be estimated.

1 Introduction

Prediction of aerodynamic characteristics of air vehicles is critical to prediction of their flight performance. These aerodynamic characteristics can be determined in a number of ways, classified as:

- Empirical
- Experimental
- Theoretical/Computational

Early in the design process, when a large number of configurations need to be rapidly evaluated against the requirements empirical approaches are most commonly used because they can be applied rapidly. Examples of the more common quasi-empirical databases for estimation of stability and control derivatives include DATCOM [3] and Engineering Sciences Data Units (ESDU). There are however a significant number of limitations with these methods, not the least of which is the limitations in the experimental database that form the basis of such methods, along with the simple theoretical relations which are used. Furthermore, such databases are generally based on generic, simplified geometries which may or may not capture the dominant characteristics of the vehicle under consideration.

The degree of error that may be expected using empirical methods vary greatly depending on the configuration and the characteristic which is being sought. Typically, the more unconventional the configuration the lower the accuracy of these methods. In terms of derivatives, prediction of static longitudinal derivatives can be quite accurate, whereas prediction of lateral directional derivatives is hindered by the typically coupled nature of roll and yaw motion. Critical roll and yaw derivatives such as roll-due-to-sideslip (C_{l_β}) and yaw-due-to-sideslip (C_{n_β}) are often very poorly estimated due in large part to the strong secondary interference effects of the fuselage and fin. Dynamic derivatives are in general even more poorly estimated, sometimes being orders of magnitude off and even of the wrong sign. The major derivatives, and error estimates, are given in Table 1.

Table 1 Comparison of conceptual design tools

Derivative	Typical error
Longitudinal	
C_{m_α}	Fair
C_{m_q}	Not useful
$C_{m_{\dot{\alpha}}}$	Not useful
Lateral-Directional	
C_{Y_β}	Fair
C_{l_β}	Not useful
C_{n_β}	Poor
C_{Y_p}	Very good
C_{l_p}	Good
C_{n_p}	Fair
C_{Y_r}	Fair
C_{l_r}	Poor
C_{n_r}	Fair
Control	
$C_{m_{\delta e}}$	Good
$C_{Y_{\delta r}}$	Fair
$C_{l_{\delta r}}$	Not useful
$C_{n_{\delta r}}$	Not useful
$C_{l_{\delta a}}$	Not useful
$C_{n_{\delta a}}$	Not useful
Key:	Very good $< 10\%$
	Good $10 <$ Error $< 20\%$
	Fair $25 <$ Error $< 50\%$
	Poor $50 <$ Error $< 100\%$
	Not useful $> 100\%$

Later in the design process far more accurate methods such as comprehensive wind tunnel testing is performed, at least for manned aircraft. The cost and time required however is generally prohibitive very early in the design process. For UAVs no wind tunnel testing may be performed at all due to cost constraints and the need to concentrate development on critical systems issues. This lack of a validated aerodynamic database hinders the development of accurate simulation models for operator training. [2]

Theoretical approaches range from very simple, quick methods to CFD-type methods that are more accurate but require considerably more setup and runtime. The relative characteristics of these three approaches is summarised in Table 2.

The purpose of this work was to examine the feasibility of captive carry testing of subscale aircraft. Captive carry testing here refers to the testing of a subscale vehicle (or perhaps fullscale in the case of small UAVs) mounted on the top of a car. Emphasis has been placed on testing of UAVs for three principle reasons:

- The budget available for aerodynamic modelling of UAVs is normally very limited, often preventing more accurate (but expensive) wind tunnel tests.
- Particularly for unconventional configurations, the handling qualities are highly uncertain. Also, a means of testing stability augmentation systems without the risk of flight testing would be of benefit in such cases.
- It may be possible to test UAVs in fullscale (or almost fullscale) and hence effectively replicate the flight Reynolds number and avoid the cost of building a special test model.

2 Captive Carry Testing

The idea of testing subscale aircraft models on ground vehicles is not unique. In both examples of published information on captive carry testing known to the authors, the purpose was to evaluate unconventional configurations in as realistic an environment and as rapidly and inexpensively as possible. Tests at Stanford University (USA) on unconventional airliner concepts used a car-top captive carry testing approach to evaluate stability augmentation systems [4],[5]. In this work the air vehicle was allowed to rotate about all three axes. Another published study of a joined wing configuration used a mounting over the front bonnet of a vehicle, partly in order to minimise any aerodynamic disturbance from the car [1]. In this instance, the air vehicle was free to rotate in pitch and yaw.

In both of these published examples, the method was recognised as having potential and as a valuable complement to existing array of test and prediction techniques. The purpose of the present work was to attempt to further develop

Table 2 Comparison of conceptual design tools

Prediction Method	**Setup Cost**	**Iteration Cost**	**Accuracy**	**Design Process Applicability**
Empirical	Low	Low	Low	Early
Wind tunnel	High	High	Very high	Mid/Late
CFD	High	Low	High (once validated)	Mid/Late

the approach to ascertain exactly which characteristics could be reliably determined.

3 Goals and Approach

The goals of this work were to demonstrate the feasibility of cartop testing to:

- Determine a vehicle's basic handling qualities and particularly any areas of concern without risking the vehicle itself as in free flight.
- To determine the feasibility of measuring stability and control characteristics (both in terms of force and moment derivatives and control surface effectiveness).
- To establish a vehicle's trim setting before free flight.

These goals were approached in a pragmatic manner with an emphasis on using cheap, readily available components wherever possible.

4 Cartop Environment

In order to ascertain the feasibility of the approach a number of factors specific to the cartop environment were studied: these being the flowfield distortion as a result of the presence of the car and the vibration as a result of being rigidly attached to the car.

4.1 Flowfield

In the case of the flowfield study a tufting grid was constructed in order to visualise the flow over the vehicle. The tufting grid was mounted at various longitudinal positions on the vehicle, as shown in Fig. 1. The test could be monitored and imagery recorded via a small digital "webt't' camera mounted on the side of the frame. Additional imagery was taken from cameras alongside the road. These means of photographing the tufting grid proved adequate to gain a reasonable qualitative understanding of the flow direction, an example is shown in Fig. 2. This simple test, performed at various vehicle speeds and with the grid at different longitudinal positions confirmed that the vehicle only disturbs a layer of air up to about 300mm from the top of the vehicle. It was therefore concluded that the vehicle would not cause significant flow distortion if the test model is set outside this region.

Fig. 1 Tufting grid mounted on vehicle

4.2 Vibration

An understanding of the vibration environment was desired for a number of reasons but primarily to determine whether there would be substantial acceleration transients which could disturb the

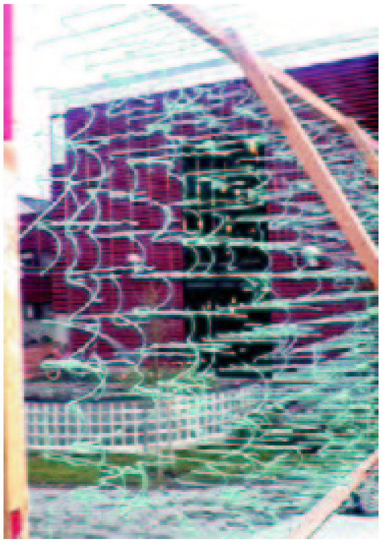

Fig. 2 Tufting grid indicating flow uniformity

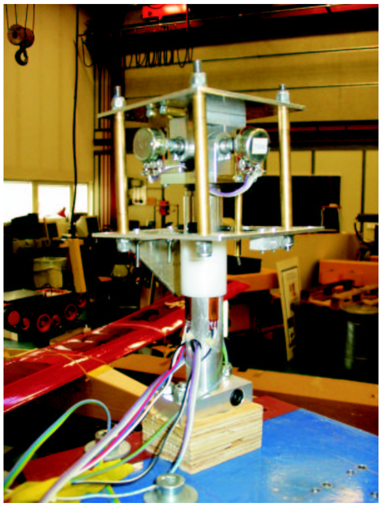

Fig. 3 Three-axis gimbal

test vehicle's motion and secondly to determine whether force and moment measurement would be possible in such an environment.

For this study a 1-axis 5g accelerometer was attached rigidly to the roof rack upon which the aircraft and tripod would be mounted such that the z-axis component of acceleration could be measured. A range of road surfaces and vehicle speeds (40-90 km/hr) were evaluated. The test results indicated that the peak accelerations were within ±0.2g and the vibrations concentrated around 47 and 68 Hz, independent of vehicle speed. This information was considered desirable for future use of dampers to reduce this vibration.

5 Rig Design

The rig itself is a gimbal free to rotate about pitch, roll and yaw and is modelled on three-axis computer joysticks. Small locking screws can fix the gimbal about any one or more axis for particular tests. In order to measure the aircraft's position potentiometers are incorporated into the gimbal. The gimbal setup is shown in Fig. 3 and 4. The gimbal external geometry was set by the size of the inertial measurement unit (IMU) used in the authors' UAVs. To minimise position corrections the IMU is typically located on or very close to the centre of gravity. Given that the aircraft must rotate about its centre of gravity to obtain realistic dynamic motions and for measured forces and moments to be decomposed it was deemed convenient to make the IMU and gimbal interchangeable. In this way, the only modification needed to the air vehicle was an access hatch underneath the CG and local strengthening. The concept is thus that the captive carry test aircraft can subsequently be used for free flight also.

The gimbal was constructed largely of aluminium. Unfortunately, in part due to its small size this results in a gimbal with insufficient strength to withstand peak loads occurring for example in wind gusts when the vehicle is stationary. It was found that these loads, imparted when the vehicle is stationary are in general much more critical than the loads when the vehicle is moving.

Basic handling qualities evaluations can be performed simply with an air vehicle with instrumented control surface position data and the potentiometers in the rig to measure pitch, roll and yaw. In order to attempt to measure forces and moments however, strain gauges were fitted to the gimbal shaft and strain gauge load cells were fitted longitudinally and laterally to measure pitch and roll moments respectively. The possibility to fit a load cell vertically to allow measurement of the yawing moment also exists, although not tested in this work. As part of

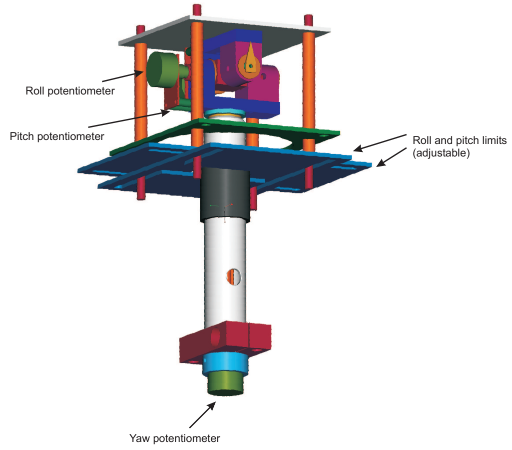

Fig. 4 CAD model of gimbal, indicating principal components

the desire to minimise costs, the load cells were cheap units taken from readily available kitchen scales. The accuracy was deemed to be more than acceptable for determining the feasibility of the method (the scales had a resolution of 0.1 gram and range up to 5 kg).

The purpose of the load cells was to measure pitch, roll and yaw moments by preventing rotation of the vehicle about the axis being measured. The load cells were attached to the gimbal itself with a rod with ball joints and turnbuckle such that the test angle (pitch, roll or yaw) could be varied as required (see Fig. 6). Transverse forces (X, Y and Z directions) were desired in order to determine the lift and drag forces. This was to be achieved through the use of strain gauges applied to the legs of the tripod. Clearly the feasibility of this approach was very much dependent on achieving a steady, non-vibrating motion of the air relative to the test vehicle.

6 Test Results

The results of the initial tests presented here are for a small, lightweight (under 5kg) aircraft of conventional configuration, as shown in Fig. 5. Stall speed of the aircraft is in the order of 35 km/hr. All results are presented for pitch only as data in roll and yaw has proven to be more difficult to obtain and is the subject of ongoing

Fig. 5 Captive carry rig and test vehicle

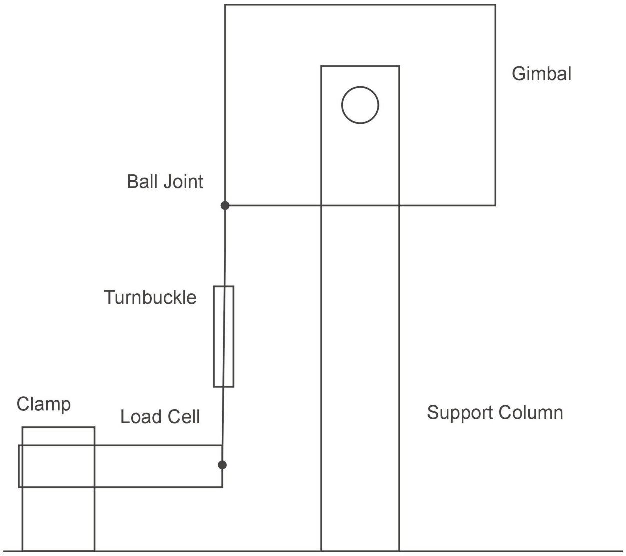

Fig. 6 Load cell attachment for moment measurement

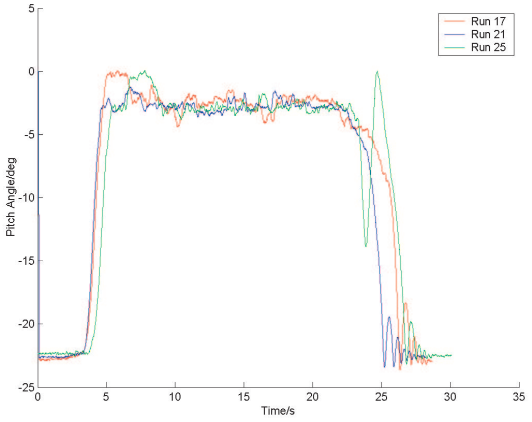

Fig. 7 Pitch trim of aircraft with neutral elevator deflection

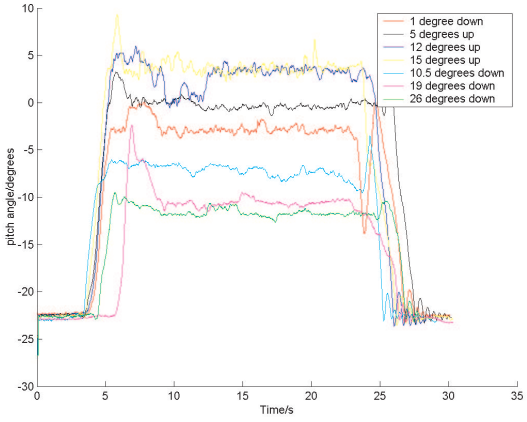

Fig. 8 Elevator effectiveness tests

work.

6.1 Repeatability

In order to determine the repeatability of the method a number of test runs were conducted with no throttle, all axes free to rotate and a vehicle speed of approximately 40 km/hr to determine the trim with neutral elevator deflection. Data for the pitch angle was gathered at 1000 Hz and a 100 point moving average used to smooth the data. Shown in Fig. 7 is the results obtained over three test runs in this condition. The data reflects the initial acceleration of the car and subsequent stabilisation of the speed over approximately 10 to 20 seconds followed by deceleration to stop. It can be readily observed that the aircraft obtains a nose down trim of about 3° in all three test runs indicating that the results are indeed repeatable.

6.2 Elevator Effectiveness

In a similar manner to the repeatability tests, test runs were performed with fixed non-zero elevator deflections, the results of which are shown in Fig. 8. Again, the stabilised test condition is in the region from approximately 10 to 20 seconds.

By reducing the data as shown in Fig. 9 very good correlation can be seen between elevator angle and pitch angle (note that pitch and angle of attack are coincident for captive carry tests). This data serves to demonstrate the feasibility of the method as a tool useful for insight into the control surface effectiveness.

6.3 Dynamic Response

The dynamic response to pitch doublets is shown in Fig. 10. Such dynamic tests demonstrate the highly damped short period mode (note that no phugoid mode is possible because the vehicle is constrained in translation). The delay in pitch response and lack of oscillation after neutralising the control is clearly evident (and repeatable) from this test.

6.4 Force and Moment Measurement

The vibration transmitted from the car to the tripod, combined with variation in the vehicle speed resulted in meaningless force measurement using the strain gauges. Further testing is required to attempt to isolate the tripod from such external effects, although initial attempts have proven discouraging. In any case, the measurement of forces while clearly useful for performance prediction, does not affect the handling qualities which is the primary objective.

Installation and operation of the moment measurement load cells (Fig. 5) was a complicated procedure due to the small space available,

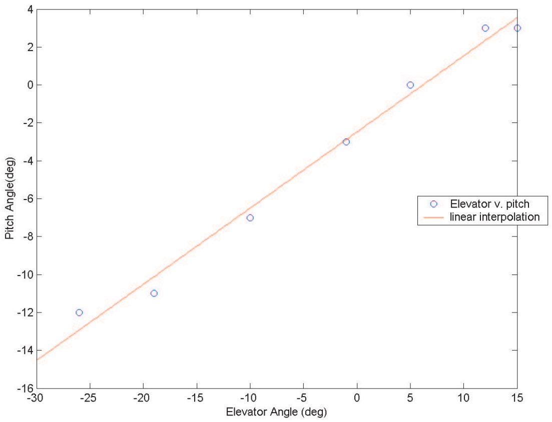

Fig. 9 Elevator effectiveness correlation

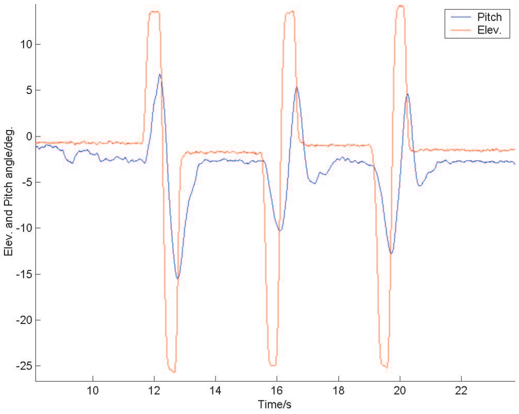

Fig. 10 Elevator control doublets

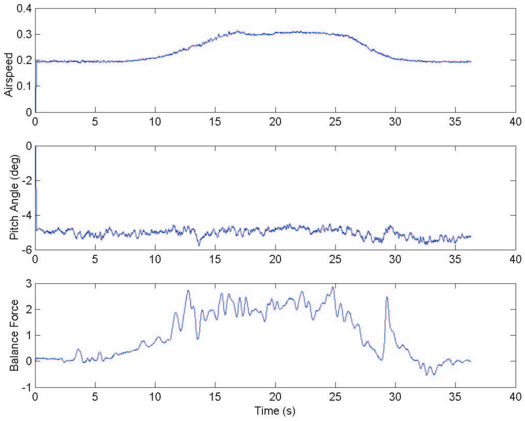

Fig. 11 Pitching moment measurement

the need to allow the connection to be adjusted easily for different angles and the loads which it must withstand. Fig. 11 shows the measured force at the load cell (from the geometry of the setup this can be readily converted to pitching moment) with a fixed elevator deflection during a run. Note that the pitch angle remains fixed (as the aircraft is constrained in pitch to the load cell) and the force required at the balance to keep the aircraft held in pitch corresponds well with velocity. Brief tests were subsequently performed which confirmed that this data was both repeatable and a change in pitching moment could be readily detected with varying elevator deflections. However, the loads imposed on the moment linkage was such that it regularly failed and hence redesign is necessary before more conclusive results can be determined in this regard.

7 Conclusion

The basic feasibility of the technique has been demonstrated such that aircraft trim and controllability can be determined with confidence using this approach. For such basic handling evaluations, the method would appear to offer the benefit of reducing risk before flying an unconventional configuration. It may be anticipated that control systems could also be tested rapidly and with low risk using such an approach.

The effect of wind was found to be minimal once the vehicle was moving. However, when stationary to mount or adjust the rig the aircraft could rapidly swing into the prevailing wind and cause damage to the rig or measurement linkages. The critical strength requirement is thus not the aerodynamic loads induced by the aircraft but rather the loads from the aircraft swinging around on the rig when stationary.

Determining quantitative characteristics is challenging, and particularly for force measurement requires effective vibration isolation and steady vehicle speed. Moment measurement is significantly easier (although by no means elementary), and it is anticipated that with sturdier links and larger range load cells the moments can be readily determined, at least to the level required for initial design stages or where no better prediction technique is utilised. This is a significant result, as estimation of the control derivatives is fraught with difficulty.

Future work includes redesigning the rig to allow it to withstand greater loads, particularly in the moment measurement system. Test runs where the test speed is stabilised for a longer period of times is also anticipated, allowing for combined control inputs to effectively test the combination of controls. Vibration isolation may also aid in determining the lift and drag force, particularly at higher dynamic pressures where these loads would be more substantial.

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