# A Comparison of Spoiler Aerodynamic Characteristics as Estimated from Flight

R.A. Stuckey*

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## 1 Introduction

The aim of this research was to develop an approach for the identification of nonlinear model parameters from flight-data and then apply it to the estimation of spoiler characteristics for the F-111C aircraft. The work was completed at the University of Sydney and has been fully documented in reference [1], the major results from which will be summarised in this paper.

Nonlinear model identification generally represents a complex problem, since the structure of the model is invariably chosen by the analyst who must therefore make decisions regarding the model's completeness, or adequacy. It must be determined not only what form the model should take, but also how complex it should be to provide a sufficient representation of the true system. The linear coefficients associated with aircraft models are well established and the form of any nonlinear (higher order) terms are usually based on knowledge of the physical characteristics.

The aerodynamic characteristics of spoilers have been described as the most difficult to predict among all conventional aircraft control surfaces, due to the present general inability to accurately model separated flows [2]. To add to the problem, the analyst can never be assured of the integrity of scaled-model wind-tunnel tests, since the Reynolds numbers used are often an order of magnitude less than that experienced in real flight. Unlike most control surfaces, the induced wake is turbulent and therefore sensitive to Reynolds number differences.

The following section presents an overview of spoiler aerodynamics. Typical characteristics of the flow are discussed, as well as those pertinent to the wing-spoiler geometry on the F-111C aircraft. In section 3, the subject of model structure determination is reviewed, with particular attention to data partitioning schemes that were used in the determination of an adequate model. Section 4 provides a summary of the preliminary analysis conducted, prior to the identification. Details of the real flight-data analysis are then discussed and two identification cases are examined in detail. Finally, section 5 concludes by summarising the main findings of this work.

## 2 Spoiler Aerodynamics

In general, spoiler devices exhibit a number of intriguing characteristics since, by their very nature, they induce separated flow. This section will outline some of the more relevant characteristics of spoilers, based largely on experimental results obtained from wind-tunnel testing. In

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*Research Scientist, Air Operations Division, Aeronautical and Maritime Research Laboratory, Defence Science and Technology Organisation, PO. Box 4331, Melbourne, VIC. 3001

fact, very little research in this area has been conducted in other fields, such as computational fluid dynamics and flight testing, which was one of the primary reasons for the study.

Spoiler devices were initially employed as roll-controls, though later found a number of alternative uses, such as lift-dumping, airbraking, direct lift control and load-alleviation. They have several features that make them desirable for lateral control in aircraft. In short, spoilers:

- provide an alternative to ailerons for full roll-control - in fact, they can be more effective at high subsonic speeds and are less prone to losing their effectiveness under aeroelastic deformation;
- produce a beneficial, *proverse* yawing moment;
- permit the concurrent use of full-span flaps; and
- can be designed for effective control at high incidence angles.

Unfortunately, the full potential of spoilers as lateral control devices has not been realised due to some of the less desirable aerodynamic features they display, including:

- inherent nonlinear characteristics, becoming even more pronounced in the presence of deflected flaps;
- drag increases are introduced;
- they may cause an undesirable lag in the aircraft response; and
- the unsteady wake can cause buffeting loads to be high.

The most common type of spoiler is the “flap-type”. These are used on many transport aircraft and some military aircraft, including the General Dynamics F-111C, as illustrated in Figure 1. For moderate wing-sweep angles, Spoilers provide the primary contribution to roll-control on the F-111C - the remainder is provided by the differentially actuated stabilators. Their effectiveness can be measured by their capacity to reduce lift on the wing or, in the case of the F-111C, their rolling moment power as they are defelected alternately.

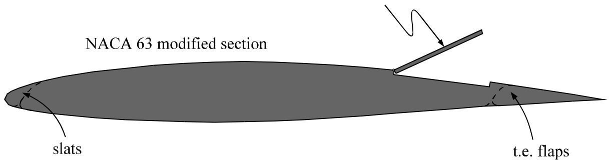

Figure 1: Airfoil with a typical flap-type spoiler

Essentially, the spoiler’s wake and hence the pressure distribution over the aerofoil is characterised by vortex shedding [3, 4]. The flowfield can change dramatically with increasing spoiler deflection and is often highly dependent on the angle-of-attack as well.

Under nominal conditions, one would expect the general behaviour of the full-scale aircraft to follow that of a wind-tunnel model. That is, for moderate angles-of-attack and subsonic Mach number, the aircraft's spoilers should exhibit nonlinear characteristics described by typical separated flow patterns. For very small control deflections, the flow may reattach aft of the spoiler, resulting in low rolling and yawing moments [5]. Figure 2 illustrates this flow field schematically.

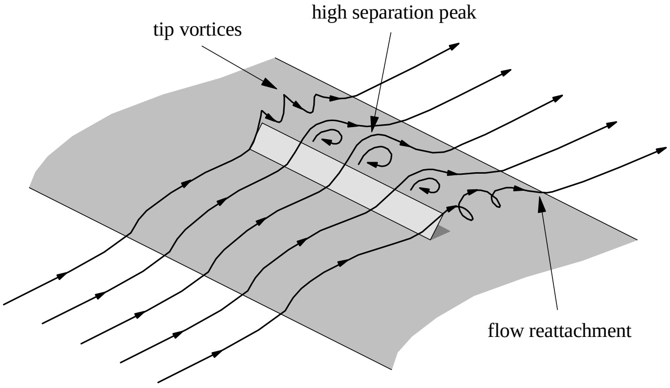

Figure 2: Local flow field over a deflected spoiler of finite span

A lack of effectiveness could be expected in this regime, although the spoilers on the F-111C are aft-mounted, so this characteristic should be small and may even prove insignificant. For larger control deflections, separation ahead of the spoiler may also occur, with reattachment on the spoiler face creating a hinge-bubble [6]. However, at typical full-scale Reynolds numbers, hinge-line separation is less likely to come about and this phenomenon should also be small, if not negligible in actual flight. Certainly, another impingement on the formation of a bubble in this region would come from the flow changes induced by the hinge-line gap on the aircraft's spoilers. Unfortunately, no substantial work has been conducted in the analysis of spoilers with hinge-line gaps and therefore, one can only make speculative assumptions concerning their effect. At high angles-of-attack, control reversal is conceivable, since the deflected spoiler at high incidence would turn the flow across the spoiler face, possibly preventing separation from occuring upstream and thus increasing the lift.

Other important factors that affect the behaviour of spoiler devices include the Mach and Reynolds numbers. It has been found [2] that the spoiler's effectiveness will typically become more positive (adverse) as the flow approaches sonic conditions. In addition, wind-tunnel tests conducted at Reynolds numbers lower than flight have been found to overestimate the effectiveness significantly. This last result is particularly relevant to the study undertaken, in which the flight-identified coefficients of the F-111C aircraft were compared against wind-tunnel data.

The effectiveness of spoilers on sweptback wings is generally reduced at moderate incidence due to the outflow along the upper surface and may become more dependent on spoiler hinge-line sweep than on wing sweep [7, 8]. At high incidence, the leading-edge wing vortices may actually aid in the reduction of effectiveness, although this was not confirmed in the wind-tunnel experiments on the F-111C aircraft model.

The model also exhibited a loss in efficiency in the high-subsonic/transonic regime, becoming highly nonlinear with respect to angle-of-attack. This is because under transonic conditions, a moderate spoiler deflection induces a lower surface shock and possibly even boundary layer separation [10].

The last effect normally present is the response lag inherent with spoiler controls [9, 10]. There are, however, two factors which minimise this effect on the F-111C: the first is the aft placement of the spoilers on the wing-chord, which tends to reduce the influence of each spoiler starting vortex as it is convected downstream; the second is the relatively slow actuation rate of the spoilers ($\omega = 160 \deg/s$, yielding a reduced frequency range of $0.004 < k < 0.01$ for the flight tests examined) which is generally lower than the rate at which lag effects start to become marked.

## 3 Model Structure Determination

To facilitate use of an equation error method, the aircraft model was formulated through a Taylor series expansion about a trim state. Each of the aerodynamic coefficients in the model could then be evaluated from the accelerations and expressed as functions of the state and control variables. The derivatives that parametrized this function comprised terms which were themselves general functions of the aircraft state. For many of these terms, a linear approximation was sufficient, however, for those coefficients in which linearisation could not be substantiated, nonlinear functions were used [11].

The nonlinear coefficients were represented by tensor-splines in one and two dimensions, since they have proven well-suited to modelling aerodynamic phenomena [12]. Spline functions are essentially a concatenation of ‘piecewise’ polynomials, whose function values and derivatives agree at the points where the polynomials join. These points are called *knots* and are defined by their projection onto the plane or axis of independent variables.

In order to identify the spline coefficients, the data first had to be sub-divided, or partitioned at each of the knots as illustrated in Figure 2. However, as the model size increased dramatically with the addition of nonlinear terms, introducing too many terms into the regression would have caused identifiability problems [13]. On the other hand, too few terms in the model might have resulted in an inadequate representation. This raised the question of required model fidelity.

Several methods which minimised the number of parameters used in the model were examined in the study, including various partitioning schemes to optimise the positioning of knots in the model.

For the purposes of the investigation, the most effective scheme was that which utilised prior knowledge - in the form of wind-tunnel model coefficients, for example - to position the knots manually. This was expected to result in a fully significant model, assuming an adequate number of data points resided in each region. That is, each of the parameter estimates would be statistically significant to the regression, as determined by a standard hypothesis test.

An alternative solution without *a-priori* information was also achieved through a nonlinear optimisation of the knots, although this proved too costly in compute-time for the quantitative analysis of flight cases planned.

In order to determine which parameters in the model were significant, a method of selection based on one or more criteria first had to be formulated. The method utilised was that of Stepwise Regression, based on a recursive algorithm in which the model is re-examined at each step. In this procedure, the independent variables are sequentially removed from the regression if their contribution is deemed nonsignificant, while candidate variables are added if their partial correlation is high. The process is allowed to continue until a fully significant model incorporating a (local) maximum number of parameters is attained.

# 4 F-111C Identification Results

In 1987, a series of flight tests were performed on the F-111C aircraft at the RAAF's Aircraft Research and Development Unit. The flight test program was carried out in two phases covering a range of conditions in wing-sweep, altitude and Mach number. In a general examination of the aircraft's flight characteristics, the data obtained from the tests were processed and analysed at the then Aeronautical Research Laboratory (ARL), as detailed in reference [15].

Further to this work, compensatory measures, including the removal of outliers and application of phase shifts, were also required to account for various instrumentation and recording errors. This was done prior to identification to avoid any spurious estimates resulting from anomalies in the data. In addition, a frequency analysis was conducted on the data in order to gain a broader perspective of the aircraft dynamics plus any external disturbances. A considerable amount of noise was found in the yawing acceleration signal, which degraded the resulting accuracy of the estimates significantly.

An examination of the correlation among the variables was also undertaken, since the presence of high collinearity is known to affect the identification process adversely [16]. The greatest degree of collinearity was exhibited between the differential-stabilator and spoiler deflections, with a lesser degree between the sideslip and rudder deflection. For those cases in which the level of collinearity was significant, a biased-estimation technique was used to alleviate the problem.

For representation of the spoilers' rolling and yawing contribution functions, first-order polynomial splines in spoiler deflection, $\delta_s$, and angle-of-attack, $\alpha$, were utilised. Several of the other derivatives also exhibited a significant variation with the angle-of-attack and were consequently represented by splines in $\alpha$ only. As mentioned previously, a number of data-partitioning approaches were examined, from which it was decided to use a conservative scheme. This scheme makes use of prior information to position the knots within the model and can thus avoid creating sparsely populated regions across the range of data.

Flight-identified results were obtained for a range of wing-sweep angles and Mach numbers. Only the lateral coefficients were examined in each case, with focus on the nonlinear spoiler terms. Two of these identification cases, constituting three flight tests, which yielded noteworthy findings are reviewed here. For the complete analysis, the reader is referred to reference [1].

A Mixed Estimation (ME) procedure [16] was employed in most of the cases, in order to bias the relevant terms sufficiently, without placing too much restriction on their estimates. In certain cases that exhibited a large amount of collinearity, a Principal Components Regression [16] was used. Rather than including them implicitly in the model equations, the sideslip-rate terms, $C_{y_{\dot{\beta}}}$, $C_{l_{\dot{\beta}}}$ and $C_{n_{\dot{\beta}}}$ were all biased toward their wind-tunnel values to avoid any associated data collinearity problems. The 'weaker' linear derivatives were also biased, but instead, toward the corresponding estimates obtained from previous Maximum Likelihood (ML) identification [15]. Due to an inherent property of this technique, these *a-priori* estimates were unbiased with respect to any noise measured in the state variables (regressors) and therefore considered closer to the true coefficients than the wind-tunnel values were. Included in this set were the sideforce derivatives with respect to roll-rate, yaw-rate, differential-stabilator deflection, rudder deflection and spoiler deflection, $C_{y_p}$, $C_{y_r}$, $C_{y_{\delta a}}$, $C_{y_{\delta r}}$ and $C_{y_{\delta s}}$ respectively ; the rolling moment derivatives, $C_{l_r}$, $C_{l_{\delta r}}$ ; and the yawing moment derivatives, $C_{n_p}$, $C_{n_{\delta a}}$. The remaining unbiased linear derivatives included $C_{y_\beta}$, $C_{l_{\delta a}}$ and $C_{n_{\delta r}}$.

Since several of the stability coefficients displayed significantly nonlinear variations with the angle-of-attack, according to the wind-tunnel results, they were approximated by first-order splines in $\alpha$ only. Unlike the previous set of derivatives, these could not be adequately represented by linear terms, particularly in the high-$\alpha$ regime. The coefficients were unbiased and consisted of $C_{l_\beta}(\alpha)$, $C_{l_p}(\alpha)$, $C_{n_\beta}(\alpha)$ and $C_{n_r}(\alpha)$. Both rolling and yawing moment spoiler coefficients were represented by first-order spline functions in spoiler deflection and angle-of-attack. Formulated as moment-contributions, they took the form: $\Delta C_l(\delta_s, \alpha)$ and $\Delta C_n(\delta_s, \alpha)$. As demonstrated by the wind-tunnel spoiler models, their contribution at zero deflection was fixed to zero. That is, $\Delta C_l = \Delta C_n = 0$ at $\delta_s = 0$ for all $\alpha$.

The primary objective in the analysis of the F-111C flight-data was to identify the nonlinear aerodynamic model, focusing on the spoilers' contribution, for a range of conditions. Since the significance of each model was of no concern in the first stage, a standard regression scheme was employed, as opposed to some stepwise procedure. The general model structure was examined more closely in the following stage, with particular attention to the significance of each term.

For each of the flight cases considered, the resulting estimates are compared against their *a-priori* values. The linear derivatives and the derivatives represented by splines in $\alpha$ are both examined with the corresponding wind-tunnel (WT) and ML estimates. Rather than displaying the spline functions, which are of little interest, their mean values (in $\alpha$) have been evaluated and compared alongside the linear coefficients. Confidence bounds were constructed for each using a critical level of 95 % and all biased terms have been highlighted.

The estimated rolling and yawing spoiler coefficients are compared against the wind-tunnel models - each plot extending to the flight-data limits in $\delta_s$ and $\alpha$. In addition, the interpolated standard error variation has been superimposed on to each surface using shading. For model axes comprising more than one partition, the standard error was based on the cross-product parameter, $C_{\mathrm{a}_{\delta s \alpha}}$ ; $\mathrm{a} = y, l, n$.

A brief discussion of the results for two identification cases are presented in the following subsections. For each case, the pertinent aspects are summarised below the corresponding figures. In addition, a comparable (lateral) dynamic response was simulated using the nonlinear model estimates from another case. For this simulation, the actual control inputs were utilised, as well as the angle-of-attack signal, in place of a full longitudinal model.

### 4.1 Flight Case P3F2E93 ($\Lambda = 35^\circ$ , 40000 ft, Mach 0.9, $\delta_s[0, 35.2]^\circ$, $\alpha[4.8, 8.9]^\circ$)

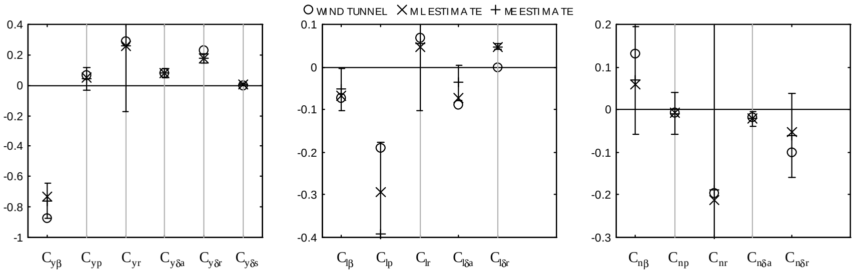

Figure 3: P3F2E93 Linear coefficient estimates

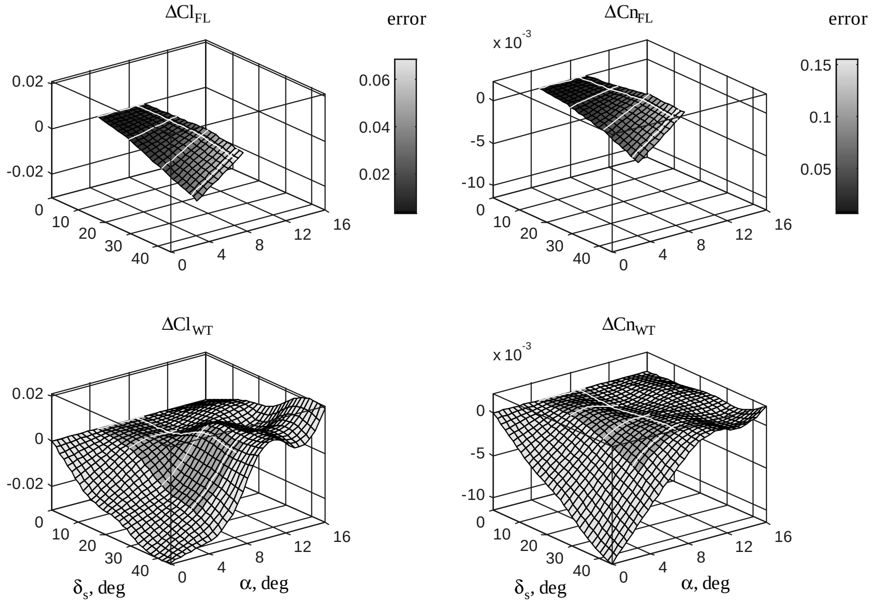

Figure 4: P3F2E93 Nonlinear spoiler coefficient estimates

Of the linear coefficients, shown in Figure 3, the estimated sideslip terms, $C_{y_\beta}$, $C_{l_\beta}$ and $C_{n_\beta}$ compared well with the ML coefficients. The roll-damping, $C_{l_p}$ was estimated larger than both wind-tunnel and Maximum Likelihood results and $C_{l_{\delta a}}$ was estimated smaller. Although the error bounds were high, the estimated yawing moment coefficient, $C_{n_r}$, correlated extremely well with both previous results.

For identification of the nonlinear spoiler model, two knots were positioned in $\delta_s$ at 12.0° and 24.0° and one knot was placed in $\alpha$ at 4.7°. This was done in order to capture the nonlinear variation with spoiler deflection exhibited by the wind-tunnel model of Figure 4. The resulting estimates of both rolling and yawing contributions compared reasonably, although their variation with $\delta_s$ was far less.

The significance of individual terms was not considered in this flight case, hence the full model - comprising all postulated coefficients - was used here.

### 4.2 Flight Cases P1F5E97, P3F1E48 ($\Lambda = 16°$, 30000 ft, Mach 0.6, $\delta_s[0, 43.9]°$, $\alpha[4.3, 12.2]°$)

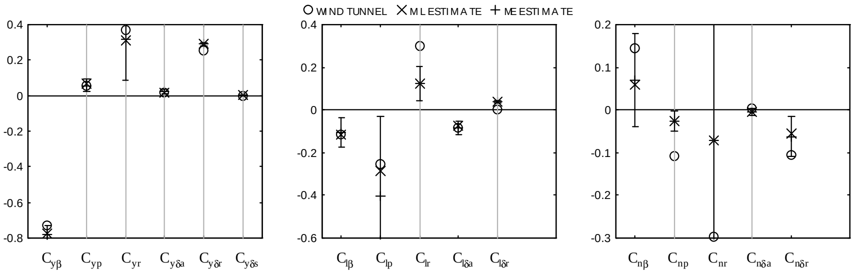

Figure 5: P1F5E97, P3F1E48 Linear coefficient estimates

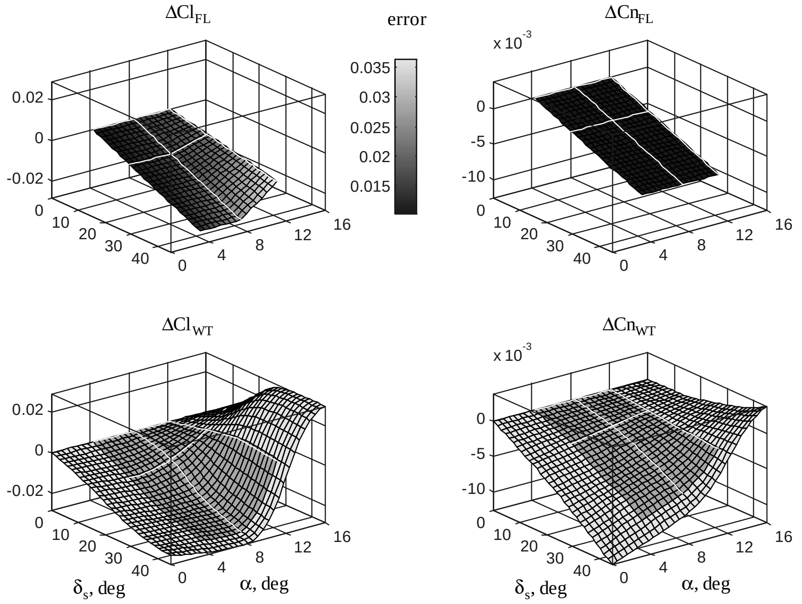

Figure 6: P1F5E97, P3F1E48 Nonlinear spoiler coefficient estimates

Again, $C_{y_\beta}$ and $C_{l_\beta}$ correlated well with both wind-tunnel and Maximum Likelihood estimates as illustrated in Figure 5. The estimates of $C_{l_{\delta a}}$ were also very close and each of the yawing-moment derivatives, $C_{n_\beta}$, $C_{n_r}$ and $C_{n_{\delta r}}$ followed their ML estimates well.

Since the data from two flights was used in this identification, covering a reasonably large range in both $\delta_s$ and $\alpha$, a more complex spoiler model was postulated. From Figure 6, it can be seen that one knot was placed in $\delta_s$ at 14.0° and one was placed in $\alpha$ at 8.5° to identify two possible nonlinearities in the model. The $C_{l_{\delta s}}$ parameters compared well with the corresponding wind-tunnel values, as did the $C_{l_{\delta s \alpha}}$ terms in all but the outermost region. That is, the sudden decrease in spoiler effectiveness was estimated much less than that from the wind-tunnel model.

Following an initial estimation, each of the coefficients in the aircraft model were tested for significance using a Stepwise Regression (SR) technique. Those terms found to have a nonsignificant contribution were consequently removed, leaving a reduced model. Hence, the variation in yaw control with angle-of-attack was eliminated from the spoiler model.

The spoilers' sideforce derivative was on average very small and was the least significant of all of the sideforce coefficients. The rolling-contribution exhibited a general decrease with increasing angle-of-attack, as illustrated in Figure 4. Figure 6 indicates that the change was less marked, however, inferring a sustained effectiveness through $\alpha$. From this and other identification cases, the characteristic sudden loss in rolling-contribution and subsequent degradation into full control reversal at high angles-of-attack was also detected. Moreover, it was found to constitute a significant effect (at 95 % confidence), although it occurred at a higher angle than observed in the wind-tunnel model.

Along with the decrease in the rolling contribution, a corresponding decrease in the yawing contribution was identified. Unlike the former term, however, no rapid change was detected with increasing angle-of-attack. Furthermore, the variation in $\alpha$ was found to be nonsignificant - also shown in Figure 6. It was concluded that the main cause of disagreement between the wind-tunnel and flight-identified results was the Reynolds number differences present in each case, which affected the spoiler's separated flow field.

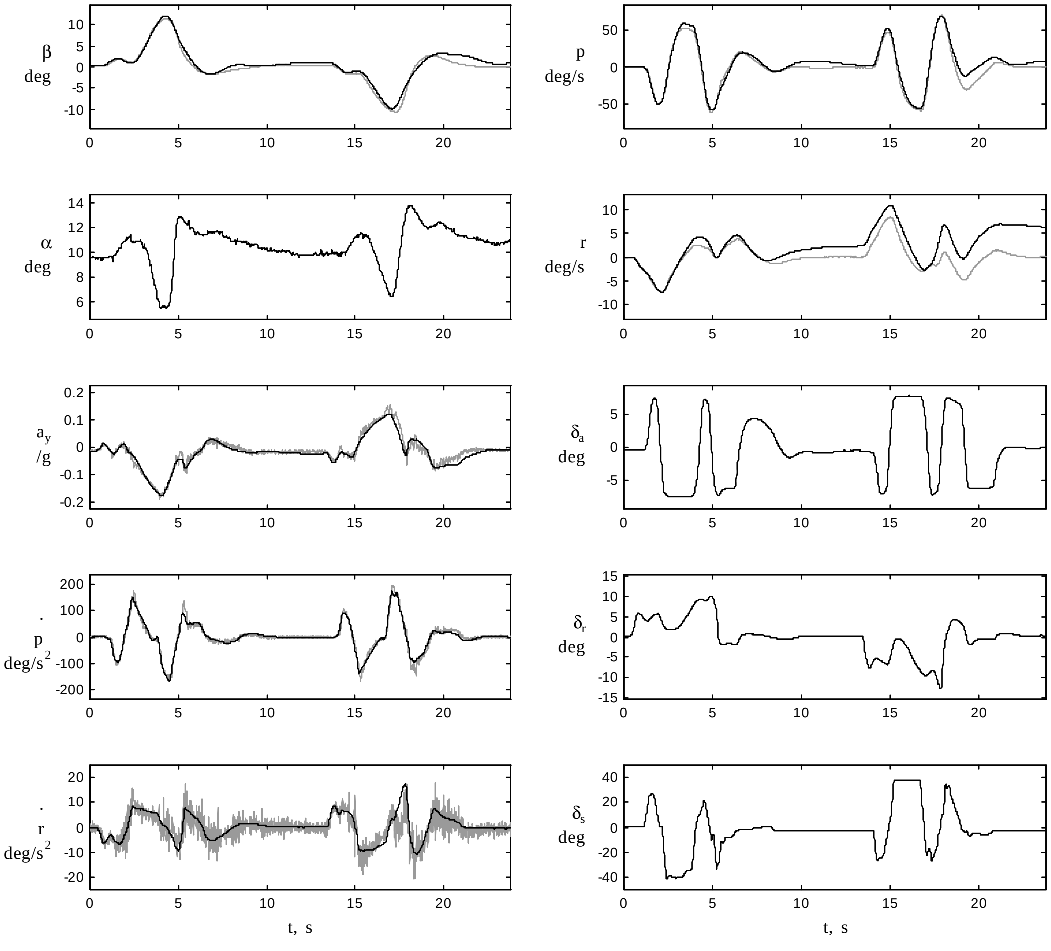

Figure 7: Flight Case P1F5E89 ($\Lambda = 26°$, 30000 ft, Mach 0.6) simulated response

A dynamic response was simulated for each of the resulting identification models, one of which is shown in the figure above (7). As with many of the flight cases examined, the manoeuvre was executed using a combined spoiler and rudder input. Aerodynamic complexities have arisen because of the high attitude at which the aircraft has been trimmed. Both linear and angular accelerations followed the measured data well. The level of measurement noise in the sensor data is clearly discernible against the computed signals, especially in the lateral and yawing accelerations. Of the state variables, the sideslip and roll rate compared generally well; the yaw rate exhibited some drift with respect to its measured path.

At this point, it is important to emphasize that the ME solution to the equation error model minimises the response (acceleration) error and not the error in the independent (state and control) variables. Therefore, any noise in these variables will bias the estimates accordingly.

## 5 Concluding Remarks

The identification strategy used in the analysis of the flight-data was essentially the same for each of the cases examined, with the exception that the partitioning scheme was tailored to each. In the majority of cases, a Mixed Estimation technique was employed, though in some cases that exhibited a high level of collinearity, a Principal Components Regression was used. Several of the lateral derivatives were represented by splines in $\alpha$ only, whilst the spoiler coefficients were formulated as tensor-product splines in both $\delta_s$ and $\alpha$.

The results obtained from the analysis of two flight have been presented, with focus on the aerodynamic behaviour associated with each aspect. In summary, the following characteristics were identified:

- the spoilers' sideforce derivative, $C_{y_{\delta_s}}$, was relatively small compared to the other sideforce terms;
- the rolling-moment contribution generally decreased with increasing $\alpha$;
- a rapid decrease in the spoilers' effectiveness was identified, although it was much less significant than suggested by the wind-tunnel data and occurred at a higher angle-of-attack;
- continuing from the above, control reversal was also detected, but it was also smaller than expected;
- a gradual decrease in the yawing moment contribution with increasing $\alpha$ was estimated - no rapid change was apparent;
- the yawing-moment contribution also changed sign (becoming adverse) at high angle-of-attack; and
- both rolling- and yawing-moment contributions generally followed the same trends as the wind-tunnel models with sweep angle and Mach number.

Lastly, using a Stepwise Regression procedure, a fully significant model for both rolling and yawing moment coefficients was obtained. This revealed that the sudden rolling moment loss identified at high $\alpha$ was, in fact, significant, although the change with $\delta_s$ was not. Likewise, the variation in the yawing moment contribution with $\alpha$ was not deemed significant and therefore omitted from the model.

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