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Using the HARV Simulation Aerodynamic Model to Determine Forebody Strake Aerodynamic Coefficients from Flight Data

Michael D. Messina
Lockheed Martin Engineering & Sciences Company
Hampton, Virginia

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National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

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Overview

A method to determine the aerodynamic increments (rolling, pitching, and yawing moments, C_l, C_m, C_n, respectively) for the forebody strake controllers added to the F/A-18 HARV aircraft was developed to validate the forebody strake aerodynamic model. The forebody strake aerodynamic model developed from data collected in the Langley 30x60 wind tunnel is implemented in all F/A-18 HARV simulations (Reference 1). The method described in this report is intended to present an overview of a process developed to extract the forebody aerodynamic increments. This report does not show how to run various simulation tools and does not present results because data were still being collected and analyzed at the time of writing.

The technique is to use attitude rates, surface position, and aircraft state information from flight data to calculate rotational accelerations using the simulation aerodynamic model. The accelerations are compared with flight data computed estimates to form a difference or error between the model and flight test. The error is then used to compute aerodynamic coefficient errors, which are summed with the model calculation. The summation results in an estimate of the aerodynamic contributions due to the forebody strakes. The forebody strake aerodynamic coefficients are correct to the extent that the basic F/A-18, HARV specific, and thrust vector control system increments are accurate.

Simulation Calculation of Rotational Accelerations

The F/A-18 HARV simulation aerodynamic model sums the aerodynamic increments from individual models to calculate total aerodynamic increments. The aerodynamic coefficients for C_l, C_m, and C_n are computed as follows:

$$\begin{aligned}
C_{l_{Total}} &= C_{l_{Low}} + C_{l_{High}} + C_{l_{HARV}} + C_{l_{TVCS}} + C_{l_{FS}} \\
C_{m_{Total}} &= C_{m_{Low}} + C_{m_{High}} + C_{m_{HARV}} + C_{m_{TVCS}} + C_{m_{FS}} \qquad (1) \\
C_{n_{Total}} &= C_{n_{Low}} + C_{n_{High}} + C_{n_{HARV}} + C_{n_{TVCS}} + C_{n_{FS}}
\end{aligned}$$

where the subscripts reflect the following definitions:

Total = total increment
Low = low angle of attack (<40°) basic F/A-18 increment
High = high angle of attack (>40°) basic F/A-18 increment
HARV = HARV specific increments
TVCS = thrust vector control system increment
FS = forebody strake increment

Once the total aerodynamic coefficients are computed, the roll, pitch, and yaw moments at the aerodynamic reference center are calculated from the aerodynamic model as follows:

$$\begin{aligned} L_{aero} &= \bar{q} S b C_{l_{Total}} \\ M_{aero} &= \bar{q} S \bar{c} C_{m_{Total}} \\ N_{aero} &= \bar{q} S b C_{n_{Total}} \end{aligned} \tag{2}$$

where $\bar{q}$ = dynamic pressure
S = reference wing area
b = reference wing span
$\bar{c}$ = mean aerodynamic chord

Moments introduced by the center of gravity (c.g.) shift from the aerodynamic reference are computed and used to adjust the aerodynamic moments. In order to calculate the moment shift, the forces at the aerodynamic reference are needed and are computed as follows:

$$\begin{aligned} F_{x_{AR}} &= \bar{q} S\{-C_{D_{Total}} \cos(\alpha) + C_{L_{Total}} \sin(\alpha)\} \\ F_{y_{AR}} &= \bar{q} S C_{Y_{Total}} \\ F_{z_{AR}} &= \bar{q} S\{-C_{D_{Total}} \sin(\alpha) - C_{L_{Total}} \cos(\alpha)\} \end{aligned} \tag{3}$$

where $C_{D_{Total}}$ = total drag increment
$C_{L_{Total}}$ = total lift increment
$C_{Y_{Total}}$ = total side force increment
α = angle of attack

The force total increments ($C_{D_{Total}}$, $C_{L_{Total}}$, and $C_{Y_{Total}}$) are computed in a fashion similar to the calculation of moments shown in equation (1).

The distance between the aerodynamic reference and the center of gravity are defined as follows:

$$\left.\begin{aligned}\Delta_x &= \frac{\left(FS_{AR} - FS_{cg}\right)}{12}\\ \Delta_y &= \frac{\left(BL_{cg} - BL_{AR}\right)}{12}\\ \Delta_z &= \frac{\left(WL_{AR} - WL_{cg}\right)}{12}\end{aligned}\right\} \qquad (4)$$

where FS_{cg} = Fuselage Station c.g.
BL_{cg} = Buttock Line c.g.
WL_{cg} = Water Line c.g.
FS_{AR} = Fuselage Station aerodynamic reference
BL_{AR} = Buttock Line aerodynamic reference
WL_{AR} = Water Line aerodynamic reference

The moment change is computed as follows using:

$$\begin{aligned}\Delta L &= Fy_{AR}\cdot\Delta_z - Fz_{AR}\cdot\Delta_y\\ \Delta M &= Fz_{AR}\cdot\Delta_x - Fx_{AR}\cdot\Delta_z\\ \Delta N &= Fx_{AR}\cdot\Delta_y - Fy_{AR}\cdot\Delta_x\end{aligned} \qquad (5)$$

The total moments about the c.g. are computed by summing the moment introduced by the aerodynamics with that introduced by the c.g. shift along with the engine thrust contributions.

$$\begin{aligned}L &= L_{aero} + \Delta L + L_{thrust}\\ M &= M_{aero} + \Delta M + M_{thrust}\\ N &= N_{aero} + \Delta N + N_{thrust}\end{aligned} \qquad (6)$$

The rotational acceleration equations of motion are defined as follows (Reference 2) and correspond to the implementation used in the simulation.

$$
\begin{aligned}
\dot{p} &= \frac{RI1\cdot q\cdot r + \frac{L}{I_{xx}} + RI2\cdot\left(q\cdot(RI5\cdot p - RI6\cdot r + p) + \frac{N}{I_{zz}}\right)}{1 - RI2\cdot RI6} \\
\dot{q} &= RI3\cdot r\cdot p + RI4\cdot(r^2 - p^2) + \frac{M}{I_{yy}} \\
\dot{r} &= RI5\cdot p\cdot q + RI6\cdot(\dot{p} - q\cdot r) + \frac{N}{I_{zz}}
\end{aligned}
\tag{7}
$$

where p = body axis roll rate
q = body axis pitch rate
r = body axis yaw rate
I_{xx} = roll moment of inertia
I_{yy} = pitch moment of inertia
I_{zz} = yaw moment of inertia
I_{xz} = roll-yaw cross coupling product of inertia

$$RI1 = \frac{I_{yy} - I_{zz}}{I_{xx}} \qquad RI4 = \frac{I_{xz}}{I_{yy}}$$

$$RI2 = \frac{I_{xz}}{I_{xx}} \qquad RI5 = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

$$RI3 = \frac{I_{zz} - I_{xx}}{I_{yy}} \qquad RI6 = \frac{I_{xz}}{I_{zz}}$$

Flight Estimates of Rotational Accelerations using Aerodynamic Model

An estimate of the rotational accelerations of the aircraft during flight testing can be made by using the simulation aerodynamic model. The estimate is as accurate as the aerodynamic model, since all aerodynamic models were developed with wind tunnel data only. In order to estimate the rotational accelerations of the F/A-18 HARV during flight, the simulation aerodynamic model is run open loop. This involves using flight data to drive all aerodynamic model inputs over time in place of parameters calculated in the simulation. The flight data inputs to drive the simulation aerodynamic model are defined below with the instrumentation parameter names from flight data shown in parenthesis:

Aerodynamic Surface and Thrust Vector Vane Positions

- Left and Right Stabilator (DHL, DHR)
- Left and Right Aileron (DAL, DAR)
- Left and Right Rudder (DRL, DRR)
- Left and Right average Leading Edge Flap (DLFLI, DLFRI)
- Left and Right Trailing Edge Flap (DTFL, DTFR)
- Differential Strake (STPR - STPL)
- Symmetric Strake(minimum of STPR or STPL)
- Left and Right Engine Top, Inboard, Outboard Vane positions (AX10C, AX11C, AX12C, BX10C, BX11C, BX12C)

Aircraft States

- Body axis roll rate (PCC)
- Body axis pitch rate (QC)
- Body axis yaw rate (RMC)
- Angle of attack (ALPHA)
- Angle of sideslip (BETA)
- Altitude (HP)
- Mach Number (IAMACHC)
- Velocity (VINF)

Miscellaneous

Left and Right Throttle Position (ICAPLLC, ICAPLRC)

The rotational accelerations that result from driving the aerodynamic model open loop are an estimate of the flight accelerations and contain inaccuracies due to the model. The aerodynamic models used in the F/A-18 HARV simulations are derived from wind tunnel data and were not corrected based on flight test results. Comparing the accelerations from equation (7) to those computed directly from flight data provides an indication of the accuracy of the aerodynamic model. Since differences exist, errors in the acceleration can be computed and used to determine the difference between flight aerodynamic behavior and the simulation aerodynamic model.

Flight Rotational Accelerations From Flight Test Data

The flight rotational accelerations can be calculated by differentiating the measured body axis rotational rates recorded from flight. The rotational accelerations are differentiated by using user-defined Matlab functions written by Keith D. Wichman of NASA-Dryden Flight Research Center. The user-defined Matlab functions are called *director.m*, *firdiff.m*, and *diffit.m* and are included in Appendix A of this report. Additional Matlab intrinsic functions are utilized along with additional user-defined functions to read and write files in the Dryden GetData compatible formats (Reference 3).

By using the rotational accelerations from flight along with those estimated from the aerodynamic model, an acceleration error can be defined as follows:

$$\begin{aligned} \dot{p}_{error} &= \dot{p}_{flight} - \dot{p}_{model} \\ \dot{q}_{error} &= \dot{q}_{flight} - \dot{q}_{model} \\ \dot{r}_{error} &= \dot{r}_{flight} - \dot{r}_{model} \end{aligned} \tag{8}$$

The error in the rotational accelerations represents the error in the aerodynamic model plus some contribution due to errors in the measured parameters.

Calculation of Forebody Strake Aerodynamic Coefficients

By manipulating equation (7) to solve for the rotational moments L, M, N, and substituting the rotational acceleration errors in equation (8), the following equations for the moment error can be formed:

$$\begin{aligned} L_{error} &= \dot{p}_{error} \cdot (I_{xx} + RI6 \cdot I_{xx} - RI6 \cdot I_{xz}) - \dot{r}_{error} \cdot I_{xx} \\ M_{error} &= \dot{q}_{error} I_{zz} \\ N_{error} &= (\dot{r}_{error} - \dot{p}_{error} \cdot RI6) \cdot I_{zz} \end{aligned} \tag{9}$$

Note that all rotational rate terms shown in equation (7) cancel because p, q, and r from flight are the same as those used to drive the aerodynamic model open loop. Therefore, no errors exist due to the rotational rates and were neglected in equation (9).

By assuming that the moment errors in equation (9) are caused mostly by errors in the strake aerodynamic model, corrected aerodynamic coefficients for the forebody strakes can be calculated as follows:

$$C_{l_{S_{flight}}} = \frac{L_{error}}{\bar{q}Sb} + C_{l_{FS}}$$

$$C_{m_{S_{flight}}} = \frac{M_{error}}{\bar{q}S\bar{c}} + C_{m_{FS}} \qquad (10)$$

$$C_{n_{S_{flight}}} = \frac{N_{error}}{\bar{q}Sb} + C_{n_{FS}}$$

The forebody strakes rotational aerodynamic coefficients computed from the aerodynamic model are added to the coefficients based on the error between flight and the model.

Limitations

The above method of computing aircraft aerodynamic coefficients based on the aerodynamic model has limitations when used with the strake aerodynamic model described in Reference 1. Whenever the flight data that was generated while the Research Flight Control System (RFCS) was active in either Strake plus Thrust Vector mode (STV) or Strake only mode (S), the results obtained should be accurate to the degree of the aerodynamic and engine models as previously discussed. When this method is used on data where the strakes were commanded open loop with the On Board Excitation System (OBES), the user needs to be aware of when the strakes are ON or OFF schedule.

For example, a differential strake deflection of 30 degrees at 50 degrees angle of attack (AOA) corresponds to strake positions of 30 degrees on the right strake and 0 degrees on the left when RFCS is in the Thrust Vector mode (TV). If the OBES maneuver was initiated while in STV or S mode, the 30 degrees differential strake deflection would result in 50 degrees on the right strake and 20 degrees on the left strake. This combination of strake deflection occurs for two reasons: the first is that OBES maneuvers are added to the RFCS control system commands. The second is because a symmetric deflection of 20 degrees is commanded by RFCS in the STV or S modes at 50 degrees AOA. The symmetric deflection is commanded by RFCS when the strakes are active to eliminate a control reversal associated with differential strake deflections less than 30 degrees. The symmetric strake deflections follow a schedule of 1 degree of symmetric strake deflection per degree of AOA starting at 30 degrees. The maximum symmetric strake deflection of 30 degrees is reached at 60 degrees AOA. When the strakes follow the symmetric deployment they are considered ON schedule (Reference 4). The 50 degree and 20 degree deflections on the right and left strake positions would only occur briefly when RFCS is in the STV or S mode, since closed loop feedbacks would adjust the strake commands in response to the OBES inputs. For this reason all OBES differential strake maneuvers are run with the control laws in TV mode. This means that the symmetric schedule built into the RFCS control laws when strakes are active will not be followed and, therefore, the strakes can be OFF schedule.

The strake aerodynamic model assumes the strakes will be ON schedule. At 50 degrees AOA, the symmetric deflection is 20 degrees as previously mentioned, and a differential deflection of 30 degrees would result in a right and left strake position of 35 and 5 degrees respectively when RFCS is in STV or S mode. The wind tunnel data implemented in the strake aerodynamic model is based on 35 and 5 degree strake positions for the right and left strakes respectively. Using flight data collected for an OBES run with 30 degrees differential strake command at 50 degrees AOA, 30 degrees on the right strake and 0 degrees on the left would mean the strakes are OFF schedule. This results in deflections that cannot be supported by the strake aerodynamic model. Therefore, flight test data used to calculate aerodynamic coefficients when the strake deflections are commanded by OBES result in deflections that cannot occur because of the symmetric schedule built into the strake aerodynamic model. The flight coefficients calculated in equation (10) will be correct, but cannot be compared directly with $C_{l_{FS}}$, $C_{m_{FS}}$, and $C_{n_{FS}}$ from the strake aerodynamic model since these results are computed OFF schedule.

Conclusion

The method described in this report to extract forebody strake coefficient increment provides a tool to analyze flight data. This tool has been used to support flight tests of the F/A-18 HARV with the Actuated Nose Strakes for Enhanced Rolling control laws. This method is in use to validate the 30x60 wind tunnel model that has been implemented in F/A-18 HARV simulations.

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APPENDIX A - Matlab User Defined Functions

director.m

```
% Read input file, this file contains the flight data body axis
% aircraft rates. (pcc - Roll Acceleration, qc - Pitch
% Acceleration, RMC - Yaw Acceleration)

gdload('temp.cmp3')

% Get bn coefficients to be used in the low-pass filter.

N = 24;wb=1/6;
[bn] = 80.*firdiff(N,wb);

% Differentiate the signal.

[pdot] = diffit(bn,pcc,time);
pdf=filter([0.1,0.1],[1.0,-0.8],pdot);
pdf=filtfilt([0.1,0.1],[1.0,-0.8],pdot);

[qdot] = diffit(bn,qc,time);
qdf=filter([0.1,0.1],[1.0,-0.8],qdot);
qdf=filtfilt([0.1,0.1],[1.0,-0.8],qdot);

[rdot] = diffit(bn,rmc,time);
rdf=filter([0.1,0.1],[1.0,-0.8],rdot);
rdf=filtfilt([0.1,0.1],[1.0,-0.8],rdot);

% Write output file which contains the accelerations before and
% after filtering along with the aircraft rates for reference
% information only.  The flight rotational accelerations pdf,
% qdf, and rdf are the only ones in determing the forebody strake
% aerodynamic coefficients.

gdwrite('temp_rates.cmp3 cmp3', 'time pdf qdf rdf pdot qdot rdot
pcc qc rmc');
```

firdiff.m

```
function [bn]=firdiff(n,wc)
% function [bn]=firdiff(N,Wc) designs an N'th order FIR
%  differentiator using the fourier method of design with a
%  Hamming window applied.  It returns the filter coefficients
%  in length N+1 vector bn.  The roll-off frequency (Wc) must
%  be between 0 < Wc < 1.0, with 1.0 corresponding to half sample
%  rate.  The order of filter N MUST BE EVEN!

% INPUTS:  Wc...Roll-off freq normalized between 0 < Wc < 1.0
%          (1.0=half-sample)
%          N....Desired filter order (MUST BE EVEN!)
% OUTPUTS: bn...Causal Filter coefficients (length n+1)
%  Satisfies the following equation:
%          y(n) = b(0)*x(n-0) + b(1)*x(n-1) + ...... + b(N)*x(n-N)

%  To obtain the filter coefficients for a specific sample rate,
%  simply multiply the vector "bn" by the sample rate in Hz;
%  (ie: bn80 = 80*bn;)
%  To view the frequency response of the filter, follow the
%  example below:
%     w=logspace(-1,3,100);
%     dt=1/80    (80 Hz example)
%     [hjw,wjunk]=freqz(bn80,1,w*dt);
%     magdb=20*log10(abs(hjw));phased=180*angle(hjw)/pi;
%     clg;subplot(211);
%     semilogx(w,magdb);title('Magnitude F.R. of filter');
%     xlabel('Frequency (rad/sec)');ylabel('Magnitude (dB)');grid;
%     semilogx(w,phased);title('Phase F.R. of filter');
%     xlabel('Frequency (rad/sec)');ylabel('Phase (degrees)');grid;
% Written by Keith D. Wichman NASA-ADFRF 5/12/92

% Check if N is even
if rem(n,2) == 1
  disp('Filter Order N must be even')
  return
end;

% Normalize rolloff freq to 0 < wc < pi, where pi is now the half
% sample rates
wc=wc*pi;

% Compute anti-causal and causal indexes
nl=-n/2:-1;
nu=1:n/2;

% Compute anti-causal (nl's) and causal (nu's) halves of T*h(n)
%  resulting in CAUSAL filter coefficients.  The following
%  equations are from the Fourier Method of design for an FIR
%  differentiator.  It can be found in Section 9.1.6 of "DISCRETE
%  SYSTEMS AND DIGITAL SIGNAL PROCESSING" by Robert D. Strum and
%  Donald E. Kirk.  (Addison-Wesley Publishing 1988)
```

```
for i=1:n/2
 txhnl(i)=(wc/(nl(i)*pi))*cos(nl(i)*wc) -
          (1/(nl(i)^2*pi))*sin(nl(i)*wc);
 txhnu(i)=(wc/(nu(i)*pi))*cos(nu(i)*wc) -
          (1/(nu(i)^2*pi))*sin(nu(i)*wc);
end;

% Form causal filter from anti-causal and causal halves shifted
txhn=[txhnl 0 txhnu];

% Apply Hamming window of appropriate order and plot coefficients
bn=txhn.*hamming(n+1)';
```

diffit.m

```
function [sigdotout]=diffit(bn,sigin,time)
% function [sigdotout]=diffit(bn,sigin,time)
%  This function computes the differentiated value (sigdotout)
%  of an input signal (sigin) using the specified FIR filter
%  numerator (bn).(filter order N => N+1 bn's)
% INPUTS:  bn.....CAUSAL filter coefficients (bn MUST BE ODD #)
%          sigin..Input signal to be differentiated
%          time..Time vector corresponding to input signal
% OUTPUTS: sigdotout..Computed derivative of signal
% NOTE: bn takes the form:
%      y(n) = b(0)*x(n-0) + b(1)*x(n-1) + .... + b(N)*x(n-N)
%  The output signal is shifted by N/2 to ensure ZERO phase shift
%  induced, ie: a NON-CAUSAL filter.  This results in N/2
%  corrupted terms at the end.
% Written by Keith D. Wichman NASA-ADFRF 5/12/92

% Determine Filter Order (bn has N+1 terms for Nth order)

n=length(bn)-1;

% Determine input signals length

long=length(sigin);

% Pad end of sigin with reflection of N/2 terms

for i=1:n/2
  padend(i)=sigin(long-i);
end;
sigin=[sigin; padend'];

% Compute signal derivative and discard N/2 terms to make
% non-causal (0 phase)

sigdotout=filter(bn,1,sigin);
sigdotout=sigdotout(n/2:long+n/2-1);

return
```

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Michael D. Messina

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The method described in this report is intended to present an overview of a process developed to extract the forebody aerodynamic increments from flight tests. The process to determine the aerodynamic increments (rolling pitching, and yawing moments, Cl, Cm, Cn, respectively) for the forebody strake controllers added to the F/A - 18 High Alpha Research Vehicle (HARV) aircraft was developed to validate the forebody strake aerodynamic model used in simulation.

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