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13. ABSTRACT (*Maximum 200 words*)

Report developed under SBIR contract. This Phase I SBIR project examines the motion and aerodynamic data associated with dynamic wind tunnel tests. Historically, the aerodynamic data measured with dynamic testing has not correlated well with actual flight data, and in general has not been used in system simulations for aircrew training or flight analysis.

An improved data reduction method is presented to extract signal data from dynamic tests. The reduction method applies a Fourier series approximation fit to oscillatory data, and a linear regression fit to steady-state data. Both methods provide good signal extraction and data smoothing. Additionally, the report documents methods and equations developed by Juri Kalviste for the handling, analysis, and simulation of dynamic data.

A prototype software program has been developed to exercise the reduction methods. The program uses a new modeling architecture that enables rapid, seamless incorporation of alternative reduction or aerodynamic modeling methods.

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*** Reference Equations are provided as supplemental documentation within each Section. ***

Summary

New mathematical methods have been developed and prototyped for the utilization of data from dynamic wind tunnel tests. These methods provide a much improved analytical toolset for flight dynamicists to better understand aircraft motion and stability under extreme maneuverability conditions. This approach is based principally on the technical work in this area by the late Juri Kalviste. The dynamic stability problem is characterized thoroughly, from data generation through practical application.

The Phase I research in this SBIR concentrated on identifying and proofing a set of analytical tools that provide visibility into the dynamic stability regime. Although several technical applications exist for the resultant dynamic data, the end focus of this research project is to create a credible aerodynamic database usable in a high fidelity 6DOF simulation. The accomplishment of that goal by the end of Phase II will have considerably furthered the technical knowledge base in this field.

The technical approach for the project can be divided into three main parts,

(1) Dynamic Data Generation Methods
(2) Data Reduction Methods
(3) Aerodynamic Modeling Methods

The core of this SBIR is the Data Reduction Methods. Necessary attention is given to Dynamic Data Generation (the source of the data to be reduced) and Aerodynamic Modeling (the application of the reduced data) in order to provide a global treatment of the end-to-end problem.

A computer-aided-engineering (CAE) software program has been prototyped in Phase I making use of the reduction algorithms developed. Once completed and commercialized, the product name will be *AeroMaster*. A new model-based library architecture has been applied to the program. Each of the three areas can be thought of as an independent software model. The models share data through well-defined data interfaces, or *model specifications*. This architecture provides a very powerful technical advantage. It allows for different models, using different methods, to be directly integrated without affecting the overall operation of the program.

For example, a new data reduction scheme can be programmed as a standalone model, then integrated into AeroMaster and immediately evaluated. From a User's standpoint, the tool provides the best of adaptability and expandability.

Dynamic Data Generation Methods

The dynamic stability parameters consist of three rotation rate effects (body rates P-Q-R), and two aerodynamic angle rate effects (α', β').

Dynamic stability data can be generated either empirically or analytically. The empirical methods include tunnel testing, flight test, and the use of analogous data (from similar configuration vehicles). The analytical methods consist of various computational flow models that consider rotational and accelerated motion.

The Data Reduction model is designed to accept time-history state data from any data generation source.

Data Reduction Methods

Generalized reduction methods have been developed to provide improved signal extraction from dynamic test data. The models use curvefit algorithms tailored to the types of motion used in rotary balance and forced oscillation tests. The two methods presented employ a linear regression fit and a Fourier-series fit. Both models incorporate smoothing and quality-of-fit features. These methods allow the practicing dynamicist to better evaluate test data and correctly choose the data format for an aerodynamic database.

Aerodynamic Modeling Methods

A generalized aerodynamic database and coefficient buildup method is presented, suitable for both linear and non-linear aerodynamic data. For dynamic stability parameters, the model incorporates a generalized vector interpolation scheme known as the Kalviste Method. The model is database-driven and designed for rapid reconfiguration.

Problem Statement

The correct modeling of vehicle aerodynamics is essential for three reasons:

(1) Technical understanding of vehicle flight behavior to perpetuate the design of more efficient, safe, and maneuverable aircraft.

(2) Training of aircrews to maximize the flight performance of a given vehicle design. This is especially important in simulator training where the core vehicle simulation should very closely match the actual vehicle behavior throughout the design operating envelope.

(3) Design of flight control systems that maintain adequate control throughout the operating envelope without limiting the full performance capability of the vehicle.

It is well understood that actual vehicle aerodynamics are influenced by the dynamic effects of rotational motion and translational acceleration. In terms of aerodynamic stability parameters, these dynamics are modeled as effects of P-Q-R and α', β'. The quantitative evaluation of the dynamic motion terms has historically been based on special wind tunnel tests. These tests include rotary balance, traditionally used for spin analysis, forced oscillation, plunging oscillation, and combined motion tests.

The dynamic data from these tests, when used to predict the motion of an aircraft maneuvering at high angles-of-attack, has failed to correlate well with recorded flight test behavior. As a result, the 6DOF simulations used by major aerospace firms for flight analysis and aircrew training do not largely incorporate the tunnel data. The special apparatus and test procedures for dynamic testing is costly, so one might question the continuation of such testing, or at least the continued use of unsuccessful analysis methods.

The dilemma is that flight test provides a very scant source of stability data, whereas tunnel test provides a vast amount of stability data. If simulations are going to accurately model dynamic effects, the data is likely to come from tunnel test. Additionally, from an engineering intuition standpoint, dynamic tunnel tests appear to be a valid approach.

From a macro viewpoint, the deficiencies could be with any of the three areas previously mentioned – tunnel tests, test data reduction, or aerodynamic modeling. On the basis of data from rotary balance tests, Juri Kalviste showed that the dynamic stability parameters from forced oscillation tests could not be treated as linear derivatives at flight conditions involving high angles of attack. He also showed that that aerodynamic modeling of tunnel data produces vastly different (and incorrect) coefficients when summed using linear interpolation vs. vector interpolation.

The solution to many difficult technical issues lies in having a fundamental understanding of the physics of the problem. Many engineering and scientific disciplines have successfully used scientific visualization as a method of providing that fundamental insight. The idea is that given a sufficient visual model of the technical data, the mind can heuristically fathom and solve the problem.

The AeroMaster software program uses that philosophy as the basis for its design. The research performed under this SBIR is developing improved math methods for reduction and aerodynamic modeling, but the software is architected to accept alternative methods as they become available from government or industry engineering organizations. It is believed that this tool will provide the necessary visibility to understand and solve the dynamic modeling issue.

1.0 Wind Tunnel Test Methods

The aerodynamic characteristics of a vehicle can be described by six nondimensional aerodynamic coefficients. These consist of three *force coefficients* and three *moment coefficients*, all referenced to the principal body axes X-Y-Z.

Wind tunnel tests are performed to measure the aerodynamics of a given air vehicle design operating at given flight conditions. The vehicle models are supported by a sting or strut apparatus, and force-moment measurements are made by mass balance or strain gauge sensors. The dimensional measurements are converted to the more useful and compact nondimensional coefficient form for development of an aerodynamic database.

Tunnel tests can be grouped into two categories, *static tests* and *dynamic tests*. For quasi-steady-state motion, the aerodynamic coefficients are functions of three effects: *flight condition*, *aircraft configuration*, and *dynamic motion parameters*.

The *flight condition* is a function of angle-of-attack (α), angle-of-sideslip (β), Mach, and altitude.

The *aircraft configuration* is a function of a given combination of control surface deflections, wing sweep position, landing gear/flap positions, etc.

The *dynamic motion parameters* represent body rotation rates and aerodynamic angular rates. The three rotational rates about the principal body axes are Roll Rate P, Pitch Rate Q, and Yaw Rate R. The two aerodynamic angle rates are Angle-of-Attack Rate α' and Angle-of-Sideslip Rate β'.

Static Tests

Static tests are a function of *flight condition* and *aircraft configuration*. As the name implies, the aerodynamics are measured with the model in a stationary condition. The test vehicle is configured with a given geometry and positioned at a predetermined angle-of-attack and angle-of-sideslip. Tunnel flow conditions determine the test Mach and altitude.

Dynamic Tests

Dynamic tests are performed to measure vehicle characteristics while undergoing motion, typically for determining spin or maneuvering behavior. The two common dynamic tests currently in practice involve either steady-state or oscillatory motion. *Rotary Balance* tests are steady-state in nature, while *Forced Oscillation* and *Plunging Oscillation* tests are oscillatory in nature.

In a *Rotary Balance* test, the model is rotated at a constant rate about an axis parallel to the freestream velocity vector of the wind tunnel. At the reference body origin (RBO), the model aerodynamic angles (α, β) are constant with respect to the airstream throughout a rotational cycle. This steady-state rotation is the wind axis roll rate. Normally this data is used for spin analysis since the rotary motion closely approximates actual spin motion. The data can also be used for maneuvering analysis. Care must be taken to ensure that it is used in the same manner in which it was measured. A vehicle's total rotation vector consists of components that may include both steady-state rotation and oscillatory terms from body PQR rates. Rotary Balance data applies only to the velocity vector component of the total rotation vector.

In a *Forced Oscillation* test, the model is positioned at a predetermined angle-of-attack, then forced to oscillate about a principal vehicle axis. The frequency and amplitude of the oscillation determines the maximum rotation rate (P-Q-R). This rotation about a body axis also causes a change in angle-of-attack (α) and angle-of-sideslip (β), which results in aerodynamic angle rate effects (α', β'). These aerodynamic angle rate terms have both rotational and translational parts. Only the rotational part is active in a forced oscillation test.

In a *Plunging Oscillation* test, the model is positioned at a predetermined angle-of-attack, then forced to oscillate along a wind axis. This measures the translational part of the aero angle rate terms.

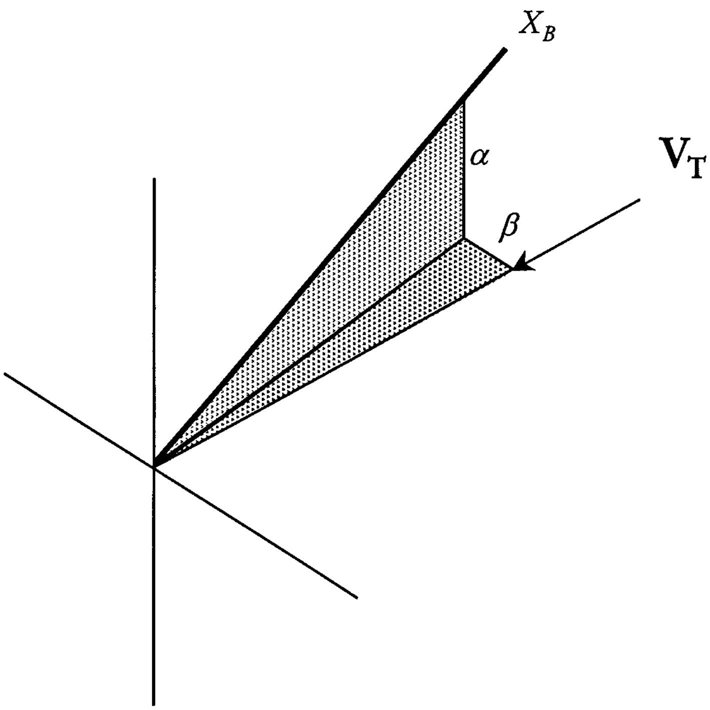
The equations for static and dynamic parameters are provided in the Reference Equations supplement to Section 1.0.

Preliminary *Preliminary*

Reference Equations

1.0 Wind Tunnel Test Methods

Static Test or Initial Conditions



X_B = *Body X-axis*

Y_B = *Body Y-axis*

Z_B = *Body Z-axis*

α = *Angle-of-Attack*

β = *Angle-of-Sideslip*

V_T = *Velocity Vector*

$$(\alpha, \beta) = f(\phi, \theta, \psi)$$

$$\sin\beta = \sin\theta \sin\phi \cos\psi - \cos\phi \sin\psi$$

$$\cos\beta = (1 - \sin^2\beta)^{1/2}$$

$$\cos\alpha = \cos\theta \cos\psi \,/\, \cos\beta$$

$$\sin\alpha = \sin\theta \cos\phi \cos\psi + \sin\phi \sin\psi$$

$$(\theta, \psi) = f(\alpha, \beta, \phi)$$

$$\sin\psi = \sin\phi \cos\beta \sin\alpha - \cos\phi \sin\beta$$

$$\cos\psi = (1 - \sin^2\psi)^{1/2}$$

$$\cos\theta = \cos\beta \cos\alpha \,/\, \cos\psi$$

$$\sin\theta = (1 - \cos^2\theta)^{1/2}$$

$$(\theta, \phi) = f(\alpha, \beta, \psi)$$

$$\cos\theta = \cos\beta \cos\alpha \,/\, \cos\psi$$

$$\sin\theta = (1 - \cos^2\theta)^{1/2}$$

$$\sin\phi = (\sin\psi \cos\beta \sin\alpha + \sin\theta \cos\psi \sin\beta) \,/\, (1 - \cos^2\theta \cos^2\psi)$$

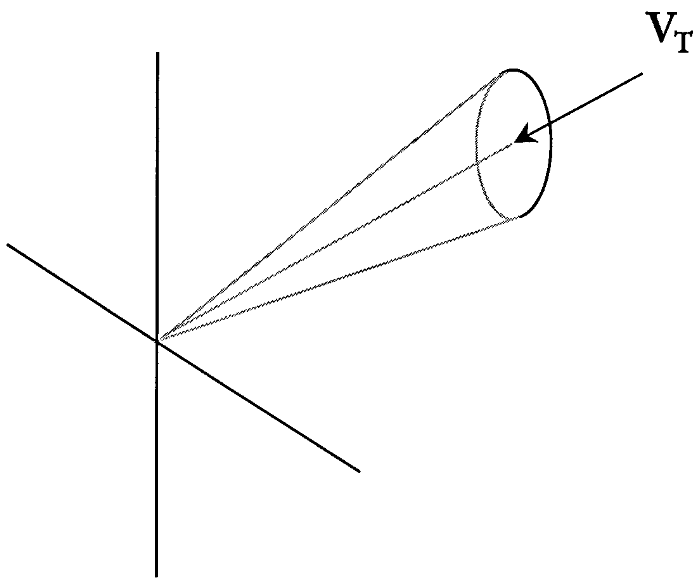
$$\cos\phi = (1 - \sin^2\phi)^{1/2}$$

Preliminary *Preliminary*

Reference Equations

1.0 Wind Tunnel Test Methods

Rotary Balance Test



V_T = *Velocity Vector*

P = *Roll Rate about Body Y-axis*

Q = *Pitch Rate about Body Y-axis*

R = *Yaw Rate about Body Y-axis*

ω = *Rotation Rate about Velocity Vector*

α = *Angle-of-Attack*

β = *Angle-of-Sideslip*

$$(\omega) = f(\alpha, \beta, P, Q, R)$$

$$\omega = P\cos\alpha\cos\beta + Q\sin\beta + R\sin\alpha\cos\beta$$

$$\omega = (P^2 + Q^2 + R^2)^{1/2}$$

$$(P, Q, R) = f(\omega, \alpha, \beta)$$

$$P = \omega\cos\alpha\cos\beta$$

$$Q = \omega\sin\beta$$

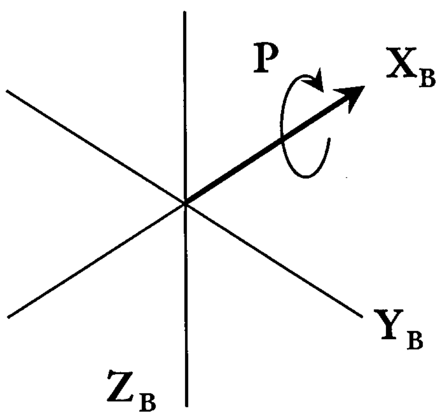
$$R = \omega\sin\alpha\cos\beta$$

Preliminary *Preliminary*

Reference Equations

1.0 Wind Tunnel Test Methods

Forced Oscillation Test about Body X-axis



X_B = Body X-axis
Y_B = Body Y-axis
Z_B = Body Z-axis

α = Angle-of-Attack
β = Angle-of-Sideslip

ω = Oscillation Frequency
ϕ = Euler Roll Angle
P = Roll Rate about Body Y-axis

$$(P_{MAX}) = f(\omega)$$

$$P_{MAX} = \omega\ \phi_{MAX}$$

$$(\omega) = f(P_{MAX}, \phi_{MAX})$$

$$\omega = P_{MAX} / \phi_{MAX}$$

$$(\phi, P) = f(\omega, t, \phi_{MAX})$$

$$\phi = \phi_{MAX} \sin(\omega\ t)$$

$$\phi' = P = \phi_{MAX}\, \omega\ \cos(\omega t)$$

$$\phi'' = P' = -\phi_{MAX}\, \omega^2 \sin(\omega t)$$

$$(\alpha, \beta) = f(\alpha_O, \phi)$$

$$\tan\alpha = \tan\alpha_O \cos\phi$$

$$\sin\beta = \sin\alpha_O \sin\phi$$

$$(\alpha', \beta') = f(\alpha, \beta, P)$$

$$\alpha' = -P\cos\alpha \tan\beta$$

$$\beta' = P\sin\alpha_O$$

2.0 Data Measurement and Reduction

Measurements in a wind tunnel are performed with sensors mounted in the vehicle support apparatus, the sensing device generally being a strain gauge. The sensors are mounted in pairs with known moment arm geometry, thereby enabling measurement of the forces and moments experienced by the test vehicle. The data are measured at some predetermined sample rate over some sample interval. Signal processing is performed on the raw data for analog-to-digital (ADC) and engineering unit (EUC) conversions.

As with all measurements, inaccuracies arise throughout the process in the form of noise, bias, histeresis, etc. The reconstruction of signals into meaningful data requires an understanding of the physics of the waveform and the source and magnitude of measurement errors. The selection of appropriate analysis techniques can provide natural correction and smoothing of raw data to better extract the inherent signal.

For the generation of an aerodynamic database, the processed parameters are stored in tables that are organized in a manner that is both readable and conducive to rapid search and interpolation. The conventional method of database organization stores non-dimensional force-moment coefficients in blocks of baseline coefficients, supplemented by blocks of incremental coefficients. The baseline coefficients represent static data for a given *flight condition*. The incremental coefficients represent static data for a given *flight condition* and *aircraft configuration*, or dynamic data for a given *flight condition*, *aircraft configuration* and *dynamic motion*.

For static and dynamic wind tunnel tests, two techniques are presented to provide smoothing and signal extraction on measured data. For non-cyclical tests (*static* and *rotary balance*), a linear regression algorithm is applied due to the steady-state nature of the data. For cyclical tests (*forced oscillation* and *plunging oscillation*), a Fourier series algorithm is applied due to the oscillatory nature of the data.

Linear Regression Algorithm

Regression methods are used to curvefit sampled data that is curvilinear ascending or descending. The four classic regression curvefits are,

Straight Line:	$y = a + bx$
Exponential Curve:	$y = a e^{bx}$, (a>0)
Logarithmic Curve:	$y = a + b \ln x$
Power Curve:	$y = a x^b$, (a>0)

All provide convenient equations to compute values for the dependent variable, y, given any value of the independent variable, x.

The linear regression fit (Straight Line) is applicable to non- cyclical wind tunnel tests. When implemented in an automated computer program, the method solves for the coefficients (a, b), and provides a quality of fit coefficient (r^2).

The values of the coefficients are indicative of the cleanliness of the sampled data. Ideally, the coefficient b should be near zero, indicating the steady-state nature of the data. The coefficient of determination r^2 should be close to 1.00, indicating a very good fit. The coefficient a is the desired steady state value of the measured parameter.

The reduction process flow is provided below.

(1) Enter n samples of (x, y) data pairs
(2) Compute the coefficient b
(3) Compute the coefficient a
(4) Compute the coefficient r^2
(5) For Rotary Balance data, compute the incremental force-moment value by subtracting the static value at the same flight condition.
(6) Compute the normalized force-moment coefficient value.
(7) Store the coefficient in the aero database table.

The linear regression equations are provided in the Reference Equations supplement to Section 2.

Fourier Series Algorithm

Fourier methods are used to curvefit sampled data that is cyclical in nature. For forced oscillation tests where the attributes of the oscillatory motion are known, a technique has been developed to fit the sampled data in a manner that provides good signal extraction and natural smoothing.

The objective of a forced oscillation test is to measure the effects of rotational or translational motion on the aerodynamic forces and moments experienced by the aircraft. Two technical issues require attention. The first is the extraction of the desired parameter from the sampled data. The second is the analysis of the parameter to determine whether the effect of motion is near-linear or clearly non-linear. This latter determination will decide how the data will be stored and retrieved in an aerodynamic database.

A tailored Fourier analysis method addresses the signal extraction and smoothing issue.

Given an array of raw time-sampled data, a sample set N is chosen, where N is the number of data points per cycle. Ideally, the value of N should be as no greater than 2x the highest expected frequency of the native signal (per Nyquist theory). Given some knowledge of the expected noise amplitude A, and desired noise error E, the number of cycles k may be computed to achieve the desired signal-to-noise (*S/N*) value. A Fourier series approximation is applied to the sample set and the Fourier coefficients extracted.

In equation form,

L	Oscillation Period	SEC
k	Oscillation Cycles	Cycles
y	Signal Amplitude	--
A	Noise Amplitude	--
E	Noise Error	--
N	No. of Pts per Cycle	--
n	n^{th} Sample Index	--
t	Time Point	SEC
a_n, b_n	Fourier Coefficients	--

Number of sample cycles determination,

$$k = A / (N \times E)$$

Fourier series approximation,

Trigonometric form,

$$F(t) = \Sigma a_n \sin(2\pi nt/L) + b_n \cos(2\pi nt/L)$$

Exponential form,

$$F(t) = \Sigma d_n e^{\cdot(2\pi jnt/L)}$$

Once the Fourier coefficients are computed from the raw sample data, the fit is complete. The frequency content and noise elimination were accommodated by the selection of N and k.

Much can be extracted from the final Fourier fit. The value of the measured signal at any time t can be directly computed. For a force or moment parameter, this represents the total value. Since the 0^{th} Fourier term is a constant that represents the value with no motion effects, this is equivalent to the static part of the parameter value. The remaining part represents the incremental effect due to motion, which is appropriate for storage in the aerodynamic database. Since the Fourier fit for any given parameter has time as the independent variable, the incremental term must be correlated with the appropriate dynamic parameter to represent an aerodynamic term. For instance, in a forced oscillation test about the X-axis, the rolling moment C_l is measured as a function of time, as is the roll rate P. The desired aerodynamic term is 'rolling moment as a function of roll rate', or $C_l(P)$, requiring a correlation of $C_l(t)$ and $P(t)$.

The reduction process flow is provided below.

(1) Choose a value of N based on motion rates.
(2) Compute the number of sample cycles k.
(3) Enter N samples of (y, t) data pairs per cycle at a sample interval of L/N over the raw data.
(4) Compute the Fourier coefficients a_n and b_n over k cycles.
(5) Subtract the 0^{th} term (static part).
(6) For motion parameters, determine rate and acceleration values.
(7) Correlate the force-moment term with the appropriate dynamic motion term.
(8) Generate values for the aerodynamic database. For near-linear data generate a derivative. For non-linear data, generate an ascending data table of the aero term vs. the motion term.
(9) Compute the normalized force-moment coefficient value.
(10) Store the coefficient in the aero database table.

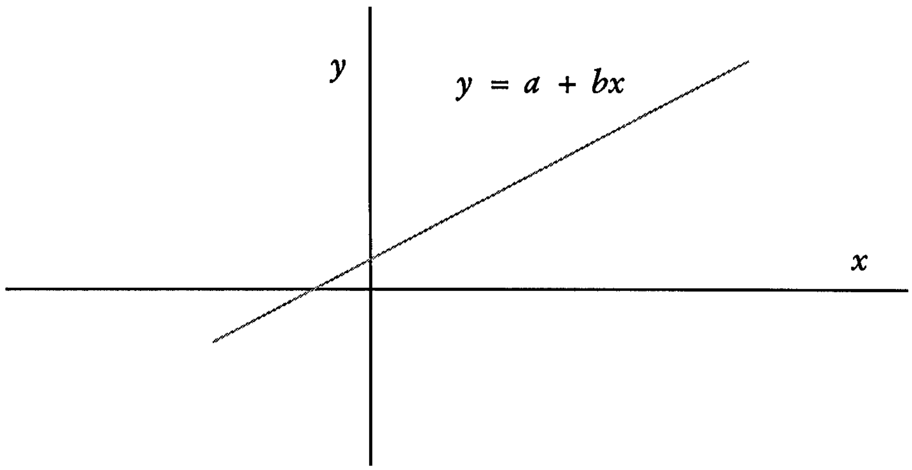
The Fourier equations are provided in the Reference Equations supplement to Section 2.0.

Preliminary *Preliminary*

Reference Equations

2.0 Data Measurement and Reduction

Linear Regression Fit



x = *Independent Variable*

y = *Dependent Variable*

$x_i\, y_i$ = *x, y Data Pairs*

a = *Y-axis Intercept*

b = *Slope*

r^2 = *Coefficient of Determination (Quality of Fit)*

$$b = \frac{\Sigma x_i y_i - \dfrac{\Sigma x_i \, \Sigma y_i}{n}}{\Sigma x_i^2 - \dfrac{(\Sigma x_i)^2}{n}}$$

$$a = \left[\frac{\Sigma y_i}{n} - b \, \frac{\Sigma x_i}{n} \right]$$

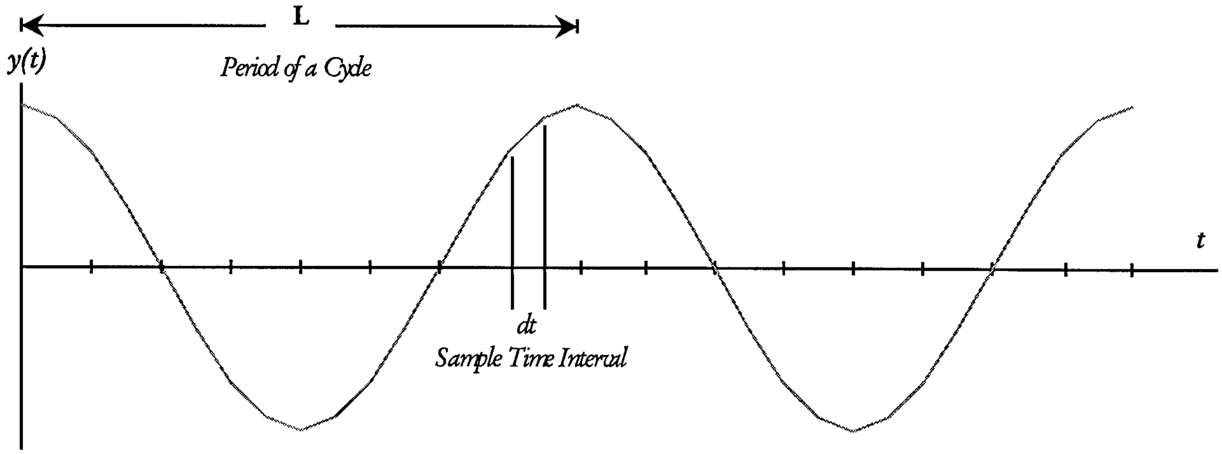
$$r^2 = \frac{\left[\Sigma x_i y_i - \dfrac{\Sigma x_i \, \Sigma y_i}{n} \right]^2}{\left[\Sigma x_i^2 - \dfrac{(\Sigma x_i)^2}{n} \right] \left[\Sigma y_i^2 - \dfrac{(\Sigma y_i)^2}{n} \right]}$$

Preliminary *Preliminary*

Reference Equations

2.0 Data Measurement and Reduction

Fourier Series Fit



$y(t)$ = Dependent Variable
t = Independent Variable, time
L = Period of a Cycle
dt = Sample Time Interval
k = Number of Cycles
N = Number of Samples

Trigonometric Form

$$a_n = 1/N\ \Sigma\ y(t) \cos(2\pi nt / L)$$

$$b_n = 1/N\ \Sigma\ y(t) \sin(2\pi nt / L)$$

$$c_n = (a_n^{\ 2} + b_n^{\ 2})^{1/2}$$

$$\cos \phi_n = a_n / (a_n^{\ 2} + b_n^{\ 2})^{1/2}$$

$$\sin \phi_n = -\, b_n / (a_n^{\ 2} + b_n^{\ 2})^{1/2}$$

$$y(t) = \Sigma\ a_n \cos(2\pi nt / L) + b_n \sin(2\pi nt / L)$$

$$y(t) = \Sigma\ c_n \cos(\underbrace{2\pi nt/L}_{\text{Frequency}} + \underbrace{\phi_n}_{\text{Phase}})$$

a_n, b_n, c_n, ϕ_n = Fourier Coefficients

$y(t)$ = Value of DV at time t

Exponential Form

$$y(t) = \Sigma\ d_n * e^{(-2\pi * j * n * t)}$$

$$y'(t) = \Sigma\ d_n * (-2\pi * j * n) * e^{(-2\pi * j * n * t)}$$

$$y''(t) = \Sigma\ d_n * (-2\pi * j * n)^2 * e^{(-2\pi * j * n * t)}$$

d_n = Fourier Coefficient
n = Sample Index, 0 to N-1
j = Imaginary Number

$y(t)$ = Value of DV at time t
$y'(t)$ = First Derivative at time t
$y''(t)$ = Second Derivative at time t

3.0 Aerodynamic Data Representation

The aerodynamic characteristics of a vehicle can be described by six nondimensional aerodynamic coefficients:

Three force coefficients	C_X, C_Y, C_Z
Three moment coefficients	C_l, C_m, C_n

Each total coefficient can be partitioned into two parts, a static coefficient and a dynamic coefficient.

The static coefficients are a function of *flight condition* and *aircraft configuration*, and represent non-rotational parameters.

The dynamic coefficients are a function of *flight condition, aircraft configuration*, and *dynamic motion parameters.*

For any of the six coefficients,

$$C_{TOTAL} = C_{STATIC} + C_{DYNAMIC}$$

where

$$C_{STATIC} = f\ (\alpha, \beta, M, h, \delta)$$

$$C_{DYNAMIC} = f\ (\alpha, \beta, M, h, \delta, P, Q, R, \alpha', \beta')$$

The generalized form is,

Coefficient Variable = f (Independent Variables)

or

$$CV = f\ (IV\text{'s})$$

In this form the coefficients are represented as a single non-linear function of all of the variables. Although this would result in a very accurate aerodynamic model, it presents an impractical solution due to the enormity of the resulting database. A more convenient method defines each total coefficient as a sum of component terms. This is known as coefficient buildup.

Two approximations are made to simplify the representation of aerodynamic data. The first approximation is to separate the total CV into incremental coefficient terms that sum to the total, where

$$CV_{TOTAL} = \Delta CV_1 + \Delta CV_2 + \ldots\ \Delta CV_i$$

The second approximations is to treat the non-linear incremental terms as products of a linear derivative and an independent state variable, where

$\Delta CV_i = f$ (Dependent Variable x Independent Variable)

or

$$\Delta CV_i = f\ (DV \times IV)$$

Care must be taken with both approximations. The first assumes that the Independent Variable (IV) of each incremental coefficient term is unaffected by the state change of another IV. The second approximation assumes that the vehicle's aerodynamics for a given ΔCV are a linear function of its corresponding IV. The decision as to which simplifying approximations are tolerable is based on the magnitude and nonlinearity of each DV. This can often be determined with good computational methods, but most commonly by wind tunnel testing.

Standard Aerodynamic Model

A generalized method has been developed that allows coefficient buildup to be done using database entry in lieu of software coded equations. Maximum flexibility is provided in the coefficient buildup process, and the result is an intuitively organized database.

Each total coefficient is computed using a "sum of products" method, or mathematically,

$$CV_{TOTAL} = \Sigma\ \Pi$$

Each incremental coefficient term may represent a constant, a linear derivative term, or a non-linear term. The symbology for each option is,

$\Delta CV_i = K$	Constant Term
$\Delta CV_i = DV_{IV} \times IV$	Linear Derivative Term
$\Delta CV_i = DV\ (IV\text{'s})$	Nonlinear Term

The buildup of drag coefficient is provided as a simple example, where the total coefficient is a function of three incremental terms, each represented as one of the three ΔCV options,

$CD = CD_O$	*Parasite Drag*	Constant Term
$+ \Delta CD_M \times M$	*Mach Drag*	Derivative Term
$+ \Delta CD\ (\alpha)$	*Induced Drag*	Nonlinear Term

The nonlinear terms can of course be functions of more than one independent variable. The common method of storing the DV data is in large tabular databases. The instantaneous DV value is obtained by performing linear interpolation based on the state value of the IV. For multiple IV's, a multidimensional linear interpolation is performed. On modern aircraft, four- or five-dimensional table lookups are common.

Kalviste Model for Dynamic Data

It was cited in Section 2.0 that data should only be used in accordance with how it was measured. Applying this principle to measured dynamic data, a method has been developed to correctly use the results of *rotary balance, forced oscillation,* and *plunging oscillation* tests in a single aerodynamic database.

This technique, known as the *Kalviste Method*, has evolved since the early 1980's. The reduced method involves resolving the total rotation vector into two components, always in the X-Y plane. The generalized method resolves the total rotation vector into three components, and considers all three body axes. One component is the steady-state rotation along the velocity vector (ω_{MOD}), while the other components are the corrected body rotation rates (P_{MOD}, Q_{MOD}, R_{MOD}). A vector addition technique is used to combine coefficient terms from different W.T. test methods, and is key to the overall correctness of the aerodynamic coefficients. Where the velocity vector and rotation vector have large separation, a difference in coefficient buildup techniques can result in a spin vs. non-spin result.

The total rotation vector is,

$$|\Omega| = (P^2 + Q^2 + R^2)^{1/2}$$

The generalized three-dimensional components are,

$$P_{MOD} = P - \omega_{MOD} \cos\alpha \cos\beta$$
$$Q_{MOD} = Q - \omega_{MOD} \sin\beta$$
$$R_{MOD} = R - \omega_{MOD} \sin\alpha \cos\beta$$

The method tests all combinations of rotation rate magnitude to determine which three components to use. One or more of the four terms will equal zero.

Once the elimination procedure is complete, the rotation rate $(\text{--})_{MOD}$ parameters are treated as normal state variables. Entry is made into the aerodynamic model and corresponding coefficient terms are computed.

To illustrate the use of wind tunnel test data, a complete coefficient buildup will be described that uses data from all dynamic tests. This method is suitable for use in a 6DOF simulation, and considers all of the rotational motion effects. The buildup uses the approximation that the total coefficient can be partitioned into incremental parts.

$C_i = C_{i\,BASE}$	*Static Test*
$+ \Delta C_i\,(\omega_{MOD})$	*Rotary Balance Test*
$+ \Delta C_i\,(P_{MOD})$	*Forced Oscillation Test (X-axis)*
$+ \Delta C_i\,(Q_{MOD})$	*Forced Oscillation Test (Y-axis)*
$+ \Delta C_i\,(R_{MOD})$	*Forced Oscillation Test (Z-axis)*
$+ \Delta C_i\,(\alpha'_T)$	*Plunging Oscillation Test (Z_W-axis)*
$+ \Delta C_i\,(\beta'_T)$	*Plunging Oscillation Test (Y_W-axis)*

α'_T	α' *due to Translation*
β'_T	β' *due to Translation*

The aero rate terms (α', β') have both rotational and translational parts. By the physics of the test motion, the *forced oscillation* data include the rotational part of the aero terms (α'_R, β'_R). The complete coefficient buildup requires inclusion of the remaining translational part. These terms can be measured in a translational acceleration tunnel test, or *plunging oscillation* test, where the aircraft attitude is fixed and the velocity vector oscillates.

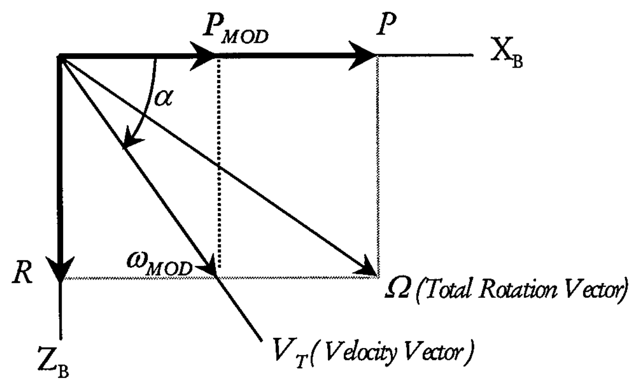
The expanded coefficient equations are provided in the Reference Equations supplement to Section 3.0.

Preliminary *Preliminary*

Reference Equations

3.0 Aerodynamic Data Representation

Aerodynamic Coefficient Model



Ω = *Total Rotation Vector*

ω_K = *Rotation Rate about Velocity Vector*

P_{MOD} = *Roll Rate about Body X-axis (Modified)*

Q_{MOD} = *Pitch Rate about Body Y-axis (Modified)*

R_{MOD} = *Yaw Rate about Body Z-axis (Modified)*

Coefficient Buildup with Dynamic Test Terms

$$C_i = C_{i\,BASE}$$

$+ \Delta C_i\,(\omega_{MOD}\, b/2V_T)$ — *Rotary Balance Test*

$+ \Delta C_i\,(P_{MOD}\, b/2V_T)$
$+ \Delta C_i\,(Q_{MOD}\, c/2V_T)$
$+ \Delta C_i\,(R_{MOD}\, b/2V_T)$ — *Forced Oscillation Test*

$+ \Delta C_i\,(\alpha_T'\; c/2V_T)$
$+ \Delta C_i\,(\beta_T'\; b/2V_T)$ — *Plunging Oscillation Test*

b = *Reference Length along Span*

c = *Reference Length along Chord*

V_T = *True Airspeed*

α_T', β_T' = *Translational part of* α', β'.

Note 1 : Forced Oscillation Test terms include rotational effects α_P', β_P'.

Note 2 : Any coefficient terms from test may be substituted with computational terms.

Kalviste Rotation Rates

$$P_{MOD} = P - \omega_{MOD}\cos\alpha\cos\beta$$

$$Q_{MOD} = Q - \omega_{MOD}\sin\beta$$

$$R_{MOD} = R - \omega_{MOD}\sin\alpha\cos\beta$$

Kalviste Vector Elimination Procedure

[Step 1] $\omega_{MOD} = P / \cos\alpha\cos\beta$

Test : $sign(Q_{MOD}) = sign(Q)$ *and* $sign(R_{MOD}) = sign(R)$
Test : $Q_{MOD} < Q$ *and* $R_{MOD} < R$
Pass : Use $P_{MOD} = 0,\ Q_{MOD},\ R_{MOD},\ \omega_{MOD}$

[Step 2] $\omega_{MOD} = Q / \sin\beta$

Test : $sign(P_{MOD}) = sign(P)$ *and* $sign(R_{MOD}) = sign(R)$
Test : $P_{MOD} < P$ *and* $R_{MOD} < R$
Pass : Use $Q_{MOD} = 0,\ P_{MOD},\ R_{MOD},\ \omega_{MOD}$

[Step 3] $\omega_{MOD} = R / \sin\alpha\cos\beta$

Test : $sign(P_{MOD}) = sign(P)$ *and* $sign(Q_{MOD}) = sign(Q)$
Test : $P_{MOD} < P$ *and* $Q_{MOD} < Q$
Pass : Use $R_{MOD} = 0,\ P_{MOD},\ Q_{MOD},\ \omega_{MOD}$

[Step 4] All fail: or all zero :
Use $P_{MOD} = Q_{MOD} = R_{MOD} = \omega_{MOD} = 0$

4.0 Sample Reduction Plots

The prototype *AeroMaster* software program was used to generate various time-history files. The data are meant to be representative of that measured in static and dynamic wind tunnel tests. The plots overlay both clean and noisy signal data in order to test the linear regression and Fourier reduction methods.

The time-history plots are provided in the Reference Plots supplement to Section 4.0.

5.0 *AeroMaster* Software Program

As of the completion of Phase I, the *AeroMaster* software is in an *alpha* pre-release state. Informal testing has been conducted on the models, with the emphasis on the reduction model. The completion of the design will occur in Phase II, as well as the formal testing. Ongoing verification will occur as actual tunnel test data is imported, and an aerodynamic database generated and simulated.

The User is encouraged to exercise the program and provide written feedback regarding features, friendliness, anomalies, errors, and overall usability.

Preliminary *Preliminary*

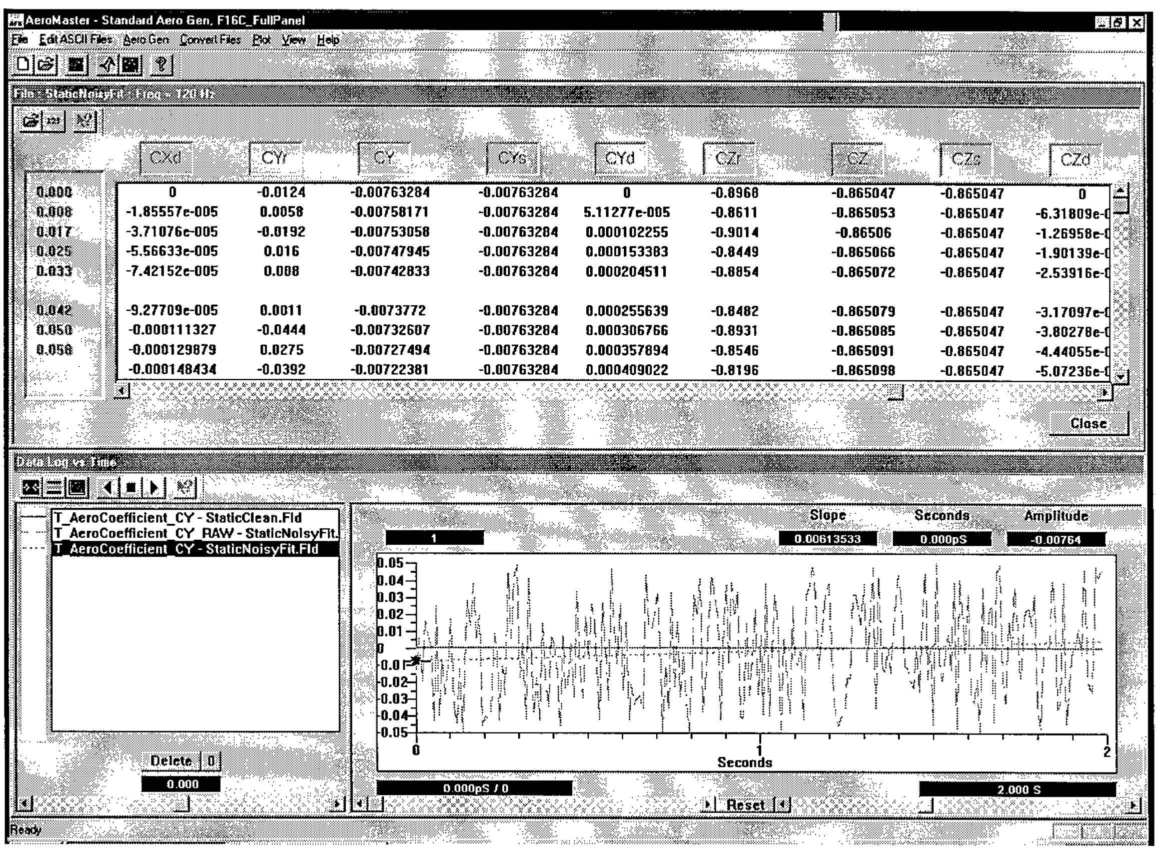
Reference Plot Data

4.0 Sample Reduction Plots

Linear Regression Fit - Static Test

A linear regression algorithm is used as the fit method for non-oscillatory data. The plot shown below is an example of static data from the AeroMaster software program. The aerodynamic data were generated with and without signal noise. The curves are labelled 'StaticClean' and 'RAW - StaticNoisyFit', respectively. The regression fit file is labelled 'StaticNoisyFit'. Ideally, the overplot of the clean signal vs. the regression fit of the noisy signal would overlay each other. In this example, the curvefit shows both a bias and a slope, indicating some residual error due to the extreme noise level (S/N of 1.0). The flow and noise parameters are listed below.

Angle-of-Attack	10°
Angle-of-Sideslip	0°
Airspeed	0.5 Mach
Motion	Static
Samples per Cycle	128
Signal-to-Noise	1.0



Preliminary *Preliminary*

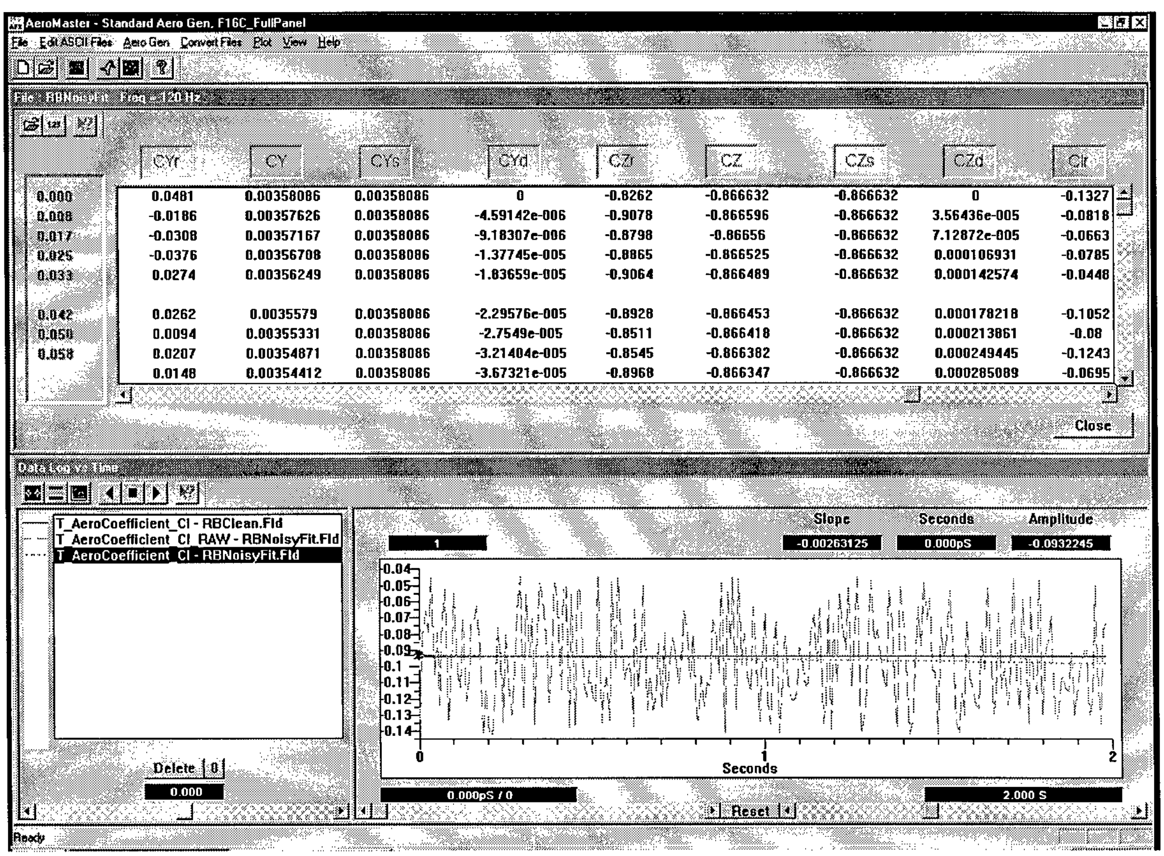
Reference Plot Data

4.0 Sample Reduction Plots

Linear Regression Fit - Rotary Balance Test

A linear regression algorithm is used as the fit method for non-oscillatory data. The plot shown below is an example of static data from the AeroMaster software program. The aerodynamic data were generated with and without signal noise. The curves are labeled 'RBClean' and 'RAW - RBNoisyFit', respectively. The regression fit file is labeled 'RBNoisyFit'. Ideally, the overplot of the clean signal vs. the regression fit of the noisy signal would overlay each other. In this example, the curvefit shows both a bias and a slope, indicating some residual error due to noise. The flow and noise parameters are listed below.

Angle-of-Attack	10°
Angle-of-Sideslip	0°
Airspeed	0.5 Mach
Motion	RB, Steady-state
Rotation Rate	7.5 RAD/SEC
Samples per Cycle	128
Signal-to-Noise	1.0



Preliminary *Preliminary*

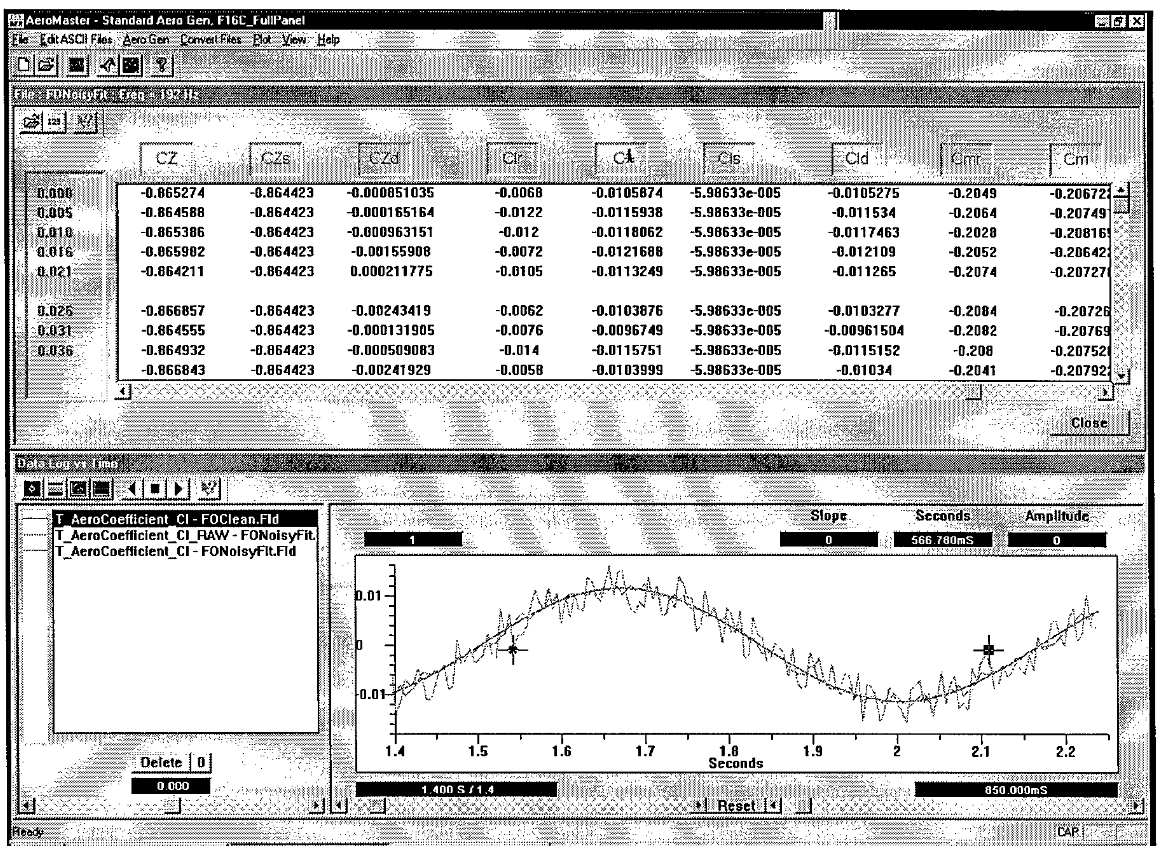
Reference Plot Data

4.0 Sample Reduction Plots

Fourier Series Fit

A Fourier series algorithm is used as the fit method for oscillatory data. The plot shown below is an example of forced oscillation data from the AeroMaster software program. The aerodynamic data were generated with and without signal noise. The curves are labeled 'FOClean' and 'RAW - FONoisyFit', respectively. The Fourier fit file is labeled 'FONoisyFit'. Ideally, the overplot of the clean signal vs. the Fourier fit of the noisy signal would overlay each other. That is the case in this example. The flow and noise parameters are listed below.

Angle-of-Attack	10°
Angle-of-Sideslip	0°
Airspeed	0.5 Mach
Motion	FO, X-Axis, Sinusoidal
Frequency	1.5 Hz
Amplitude	5°
Samples per Cycle	128
Number of Cycles	4
Signal-to-Noise	10.0



Appendix A

SBIR Phase I Progress Charts

Monthly progress briefings in the form of viewgraph presentations were provided as part of the Phase I effort. These charts are included in this appendix as part of the overall documentation for this project.

Progress Report # 1

Progress Report
CLIN 0002
Data Item A001

Improved Wind Tunnel Data Reduction Procedure
SBIR N96-019

Contract No. N00019-96-C-2025
Firm Fixed Price $74,365.19
Competitively Awarded

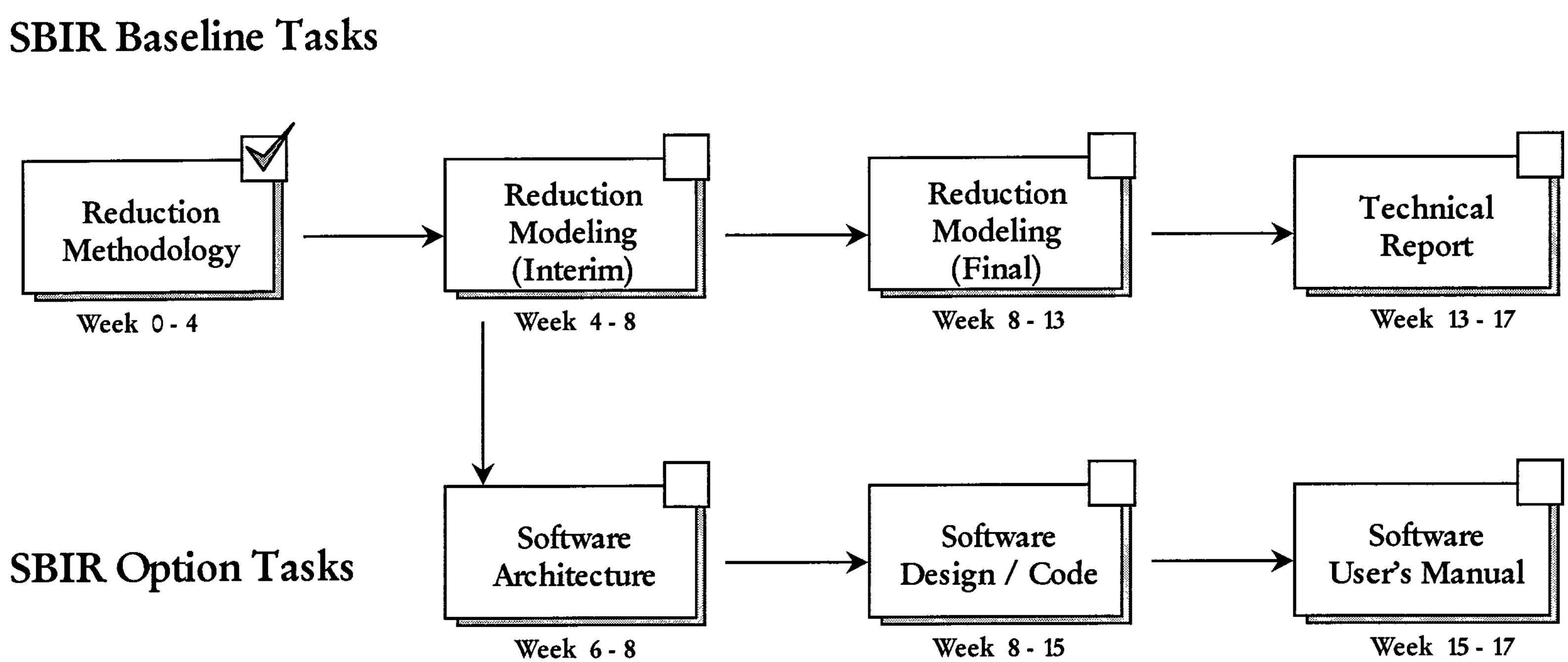
Sponsor
Robert Hanley
Naval Air Systems Command
1421 Jefferson Davis Hwy
Arlington, VA 22243

Contractor
Sight, Sound and Motion Corp.
325 East Hillcrest Dr. # 100
Thousand Oaks, CA 91360-5828

Contents

- ❑ SBIR Task Overview and Progress
- ❑ Terms and Definitions
- ❑ Statement of Problem
- ❑ Tunnel Test Descriptions
- ❑ Rotation Vector Description
- ❑ Aero Coefficient Description
- ❑ Test Data Reduction

SBIR Task Overview and Progress



Terms and Definitions

WTD	*Wind Tunnel Data* or *Water Tunnel Data.* The data can be static or dynamic. Dynamic data represent the increments due to rotational motion.
RBO	*Reference Body Origin.* Generally termed as the aerodynamic CG, this is the body coordinate about which tunnel forces and moments are referenced.
V	*Velocity Vector.* The total translational velocity relative to the airmass. For wind tunnel measurements, the vector acts through the RBO.
Ω	*Rotation Vector.* The resultant rotational velocity about the RBO, representing the combined P-Q-R rotations about the body X-Y-Z axes.
Ω_{MOD}	The component of the rotation vector (Ω) along the velocity vector. This is the parameter corresponding to rotary balance test measurements.
P_{MOD} Q_{MOD} R_{MOD}	The component of the rotation vector (Ω) along a body axis. This is the parameter corresponding to forced oscillation test measurements.
ACE	*Aero Control Effector.* A surface that deflects (δ) to produce an aerodynamic force or moment, used to control the rotational or translational motion of the vehicle.
Rotary Terms	The aerodynamic coefficient increments representing the P-Q-R rotational effects.
Aero Angle Rate Terms	The aerodynamic coefficient increments representing the $\dot{\alpha}$ and $\dot{\beta}$ effects. The Aero Angle Rates have both rotational and translational components.

Statement of Problem

- A correct understanding of air vehicle dynamic motion is necessary to successfully predict and control aircraft maneuvering at high Angle-of-Attack conditions.

- The actual physics of vehicle motion involve aerodynamic effects due to angular velocity. These effects are the result of time-dependent airflow adjustments throughout a vehicle's flowfield during rotational motion, hence are the result of the α and β of *local flow*.

- The force-moment effects of rotational motion can be closely approximated by adding rate correction terms to the aerodynamic coefficient "buildup". These terms are functions of rotational body rates (P, Q, R) and aerodynamic angle rates ($\dot{\alpha}$, $\dot{\beta}$). At high α and β, these rate correction terms are non-linear, and must be modeled as such to correctly predict vehicle dynamic motion.

- Wind-tunnel measurements of forces and moments are taken about a fixed Reference Body Origin (RBO, sometimes termed the aerodynamic CG, generally near the operating CG). These measurements need to reflect the correct non-linear behavior of forces and moments due to vehicle dynamic motion.

- This research program will achieve the following:

  (1) Using conventional wind-tunnel capabilities, define test measurement techniques that will provide data parameters necessary to model dynamic motion effects.

  (2) Design, program, and test a math model to correctly combine contributive coefficient terms from various test sources.

Tunnel Test Descriptions

The tunnel tests measure total aerodynamic forces and moments relative to a selected RBO. The Static tests establish a reference set of coefficients at selected α, β, and Mach conditions. The Dynamic test data should be corrected relative to the Static values and represent only incremental effects.

Static Tests (No Rotation)

The model is set at selected α, β, and Mach conditions. For vehicles with ACE's, individual and combined deflection tests (δ) are included to measure control effectiveness.

Rotary Balance Tests (Rotate about Velocity Vector)

The model is set at selected α, β conditions and rotated about the velocity vector. In this case, the vehicle rotation vector is coincident with the velocity vector ($\Omega = V$). When used for aero coefficient modeling, this data will represent a component of the total dynamic increment, since the actual maneuvering rotation vector will differ from the velocity vector.

Forced Oscillation Tests (Rotate about Body axes)

The model is set at selected α, β conditions and oscillated at a selected frequency-amplitude combination about a selected body axis. The body rotation rate magnitude (P-Q-R) is controlled by the selected frequency-amplitude combination. When used for aero coefficient modeling, this data will represent a component of the total dynamic increment, since the actual maneuvering rotation vector will differ from a pure body axis rotation.

Plunging Motion Tests (Translate along Wind axes)

The model is set at selected α, β, conditions and oscillated at a selected frequency-amplitude combination along a selected wind axis.

Rotation Vector Description

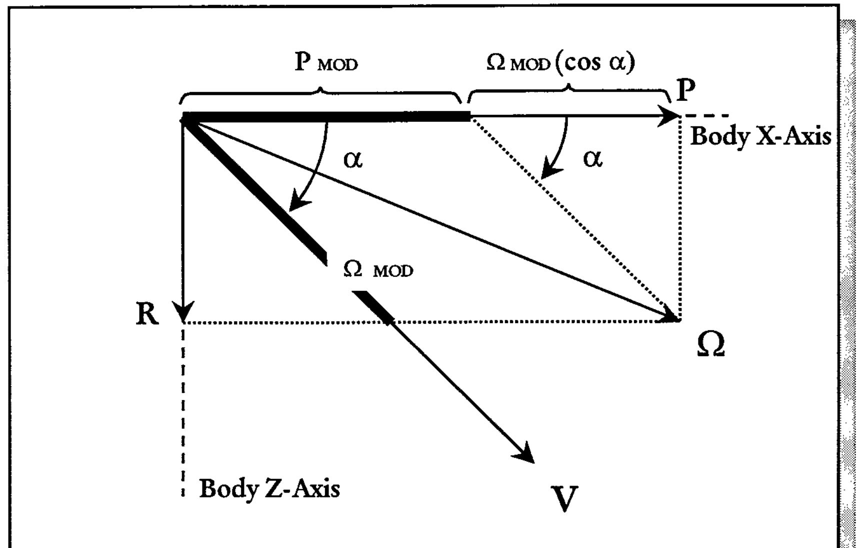
In maneuvering flight, the vehicle rotates about a Rotation Vector (Ω).

$$\Omega = (P^2 + Q^2 + R^2)^{1/2}$$

Since tunnel measurements are taken about the velocity vector and the body axes, it is convenient for the aero coefficient model to conform with these data. This is achieved by deriving the rotation vector components along those same axes.

Ω_{MOD} is the vector for **Rotary Balance** data.

P_{MOD}, Q_{MOD}, R_{MOD} are the vectors for **Forced Oscillation** data.



Rotation Vector Diagram

Lateral-Directional Rotation Equations:

For the case where the rotation vector is between the +X-axis and the velocity vector (refer to the vector diagram, where the **bold** lines indicate the components) ,

Velocity Vector Component :	$\Omega_{MOD} = R / \sin\alpha$
Body X-axis Component :	$P_{MOD} = P - \Omega_{MOD} (\cos\alpha)$
Body Z-axis Component :	$R_{MOD} = 0$

For the case where the rotation vector is between the velocity vector and the +Z-axis ,

Velocity Vector Component :	$\Omega_{MOD} = P / \cos\alpha$
Body Z-axis Component :	$R_{MOD} = R - \Omega_{MOD} (\sin\alpha)$
Body X-axis Component :	$P_{MOD} = 0$

Aero Coefficient Description

The Aero Model is the math method used to determine the total aerodynamic force and moment terms. By first defining the required parameters for a correct aero model, the reduction requirements for tunnel data also become apparent. A sample moment coefficient is presented.

The coefficient buildup of Static and Dynamic terms for rolling moment (C_l) is,

		Coefficient Terms	Tunnel Test Method
C_l	=	C_l (Base)	Static
	+	$\Delta C_l(\Omega_{MOD})$	Rotary Balance
	+	$\Delta C_l(P_{MOD})$	Forced Oscillation
	+	$\Delta C_l(R_{MOD})$	Forced Oscillation
	+	$\Delta C_l(\dot{\beta}_{TRANS})$	Plunging Motion

The terms due to vehicle rotation are highly non-linear at high angles-of-attack. Consequently, the format for non-linear Dynamic tunnel data should be identical to that of non-linear Static tunnel data.

The term due to rate of change of Sideslip ($\dot{\beta}_{TRANS}$), provides an increment for the translational effects only. The rotational effects ($\dot{\beta}_{ROT}$) are included in the rotary term (P_{MOD} , R_{MOD}) coefficients.

Aero Coefficient Description (cont.)

A generic aero coefficient buildup technique is presented that will accommodate any combination of aero terms (constant, linear derivatives, non-linear table lookup), and any source of aero data (computed, wind/water-tunnel, estimated, etc.).

$$C_i = \Sigma \Pi \quad (\text{“Sum of Products”})$$

$$C_i = S_1 + S_2 + S_3 + \ldots S_n$$

$$S_i = P_1 * P_2 * \ldots P_n$$

S_i = **Any coefficient increment (ΔC_i)**

P_i = **Any Derivative, Table-lookup, Constant, etc.**
Any Independent-Variable ($\alpha, \beta, \Omega, \delta i$, P, Q, R, $\dot{\alpha}, \dot{\beta}$)

For non-linear tunnel data in tabular form, the desired format is a rectangular table of the measured coefficient (the *Dependent Variable*, DV), organized by column-row-subgroup-group of the *Independent Variables* (IV). The conventional ordering is from fastest-changing to slowest-changing Independent Variable.

Test Data Reduction

Tunnel testing measures the aerodynamic characteristics of a vehicle at an array of flight conditions. Engineering judgment determines the extensiveness of test combinations.

Tunnel Test Conditions

Vehicle Configuration	δ_i (ACE Deflections)
Flight Orientation	α, β
Fluid Flow	**M, Re**
Dynamic Parameters	**P, Q, R** $\dot{\alpha}, \dot{\beta}$

Excluding Fluid Flow and Vehicle Configuration combinations, the essential test and database parameters relevant to dynamic motion are presented below.

Tunnel Test Method	Test Parameters	Database Parameters DV		Database Parameters IV
Rotary Balance	α, β, Ω	$\Delta C_i(\Omega)$	=	$f(\alpha, \beta, \Omega_{MOD})$
Forced Oscillation	α, β, P, Q, R	$\Delta C_i(P, Q, R)$	=	$f(\alpha, \beta, P_{MOD}, Q_{MOD}, R_{MOD})$
Plunging Motion	$\alpha, \beta, V_{ZW}, V_{YW}$	$\Delta C_i(\alpha, \beta, \dot{\alpha}, \dot{\beta})$	=	$f(\alpha, \beta, \dot{\alpha}_{TRANS}, \dot{\beta}_{TRANS})$

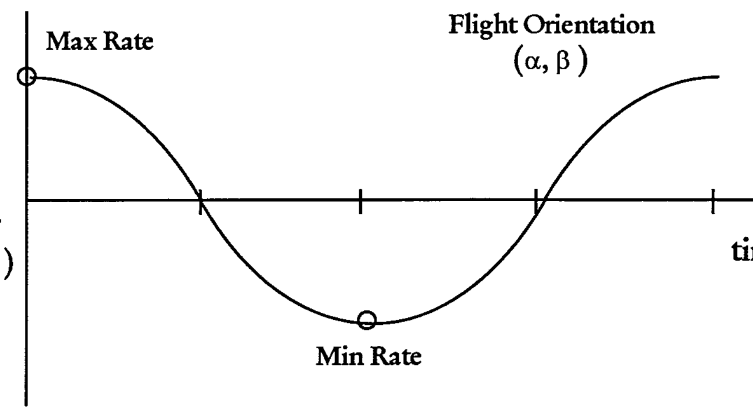
Test Data Reduction (cont.)

The aerodynamic database methods presently available from **Rotary Balance** tests are satisfactory for the recommended coefficient buildup scheme.

The desired database from **Forced Oscillation** and **Plunging Motion** tests requires that the coefficients be saved as a non-linear function of the dynamic rate parameters. Both tests involve oscillatory motion where the magnitude of the dynamic parameter (**P, Q, R,** $\dot{\alpha}$, β) depends on a selected frequency-amplitude combination.

[1] Given a selected flight orientation (α, β), select frequency-amplitude combinations to produce angular rates commensurate with the vehicle's flight envelope.

[2] Measure force-moment coefficients at Min and Max rate conditions. Record average Min-Max values over several cycles. This will provide values closest to constant-rate conditions. (See Figure)



[3] Correct measured values with static values to derive incremental values. Correct with any other flow and tunnel-peculiar adjustments.

[4] Generate a database of the Coefficient (*DV*) as a function of the Flight Orientation and Dynamic Parameter (*IV*). (See Example)

Example:

Rolling Moment Coefficient Increment due to Roll Rate

$$\Delta C_l = f(P)$$

The independent state variables are α, **R**, and **P**. For the rotation vector between the +X-axis and the velocity vector, the database of is entered with α and **P** MOD. Interpolation is performed to determine ΔC_l .

Progress Report # 2

Progress Report
CLIN 0002
Data Item A001

Improved Wind Tunnel Data Reduction Procedure

SBIR N96-019

Contract No. N00019-96-C-2025
Firm Fixed Price $74,365.19
Competitively Awarded

Sponsor
Robert Hanley
Naval Air Systems Command
1421 Jefferson Davis Hwy
Arlington, VA 22243

Contractor
Sight, Sound and Motion Corp.
325 East Hillcrest Dr. # 100
Thousand Oaks, CA 91360-5828

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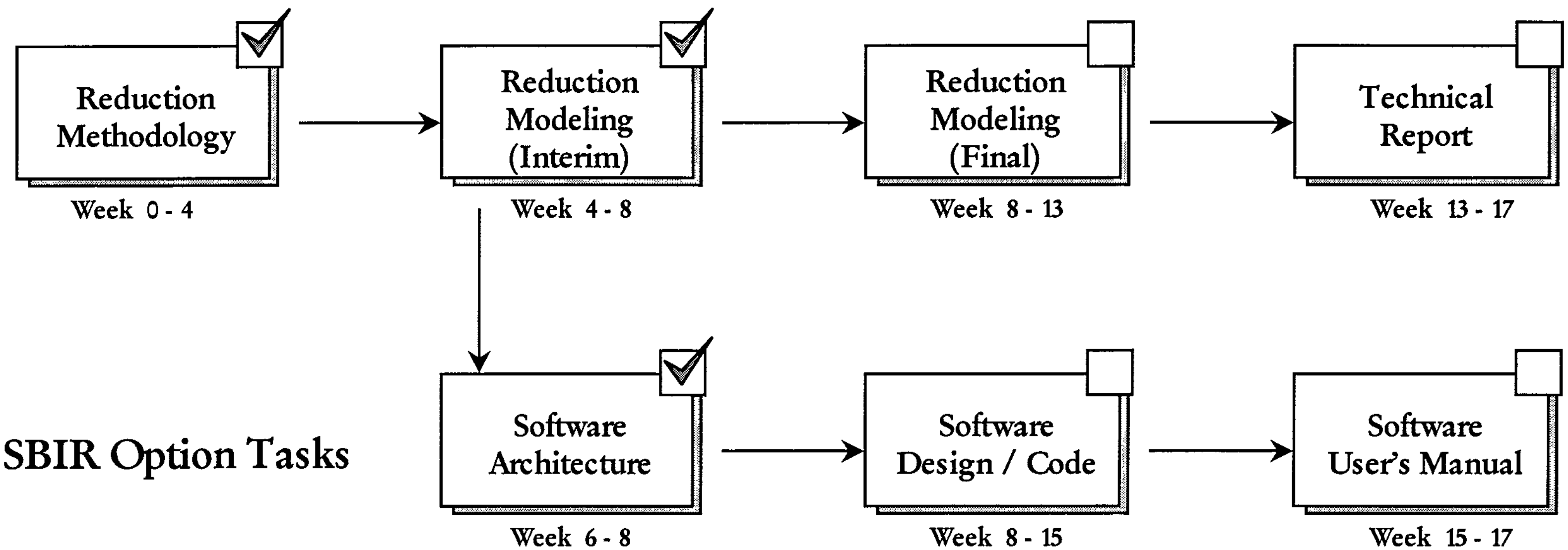
- ❑ SBIR Task Overview and Progress
- ❑ Terms and Definitions
- ❑ Reference Equations

- ❑ Software Program Description
- ❑ Software Architecture
- ❑ Software Technical Approach

SBIR Task Overview and Progress

SBIR Baseline Tasks

SBIR Option Tasks



Terms and Definitions

ABC	*Aircraft Body Coordinate* reference frame. The origin for airframe data is FS-BL-WL 0-0-0. The origin for aerodynamic data is the RBO. The origin for body motion is the instantaneous CG.
FS	*Fuselage Station.* The ABC longitudinal airframe X-coordinate. Positive aft.
BL	*Butt Line.* The ABC lateral airframe Y-coordinate. Positive to the right.
WL	*Water Line.* The ABC vertical airframe Z-coordinate. Positive up.
C.P.	*Center of Pressure.* The location on an airfoil where all resultant Lift-Drag forces act.
F_i	*Force or Moment.* Forces act on lifting surfaces based on local aerodynamic conditions (α, β, V). Local forces provide moments at the RBO based on the force vector and the moment arms to the force origin. The force origin on a lifting surface is the C.P.
C_i	*Force or Moment Coefficient.* Non-dimensionalized forms of Forces and Moments.
ω, ω_{MOD}	*Rotation Rate.* P-Q-R are respectively the body Roll-Pitch-Yaw Rates. Ω is the resultant rotation. The ω_{MOD} subscript modifier is used when an operation has been performed to determine the active terms based on the relative position of the velocity vector and the rotation vector to the body axes.
$\dot{\alpha}_{ROTAT}$, $\dot{\beta}_{ROTAT}$	*Rotational Aero Rates.* The rate of change of α or β due to vehicle rotation.
$\dot{\alpha}_{TRANS}$, $\dot{\beta}_{TRANS}$	*Translational Aero Rates.* The rate of change of α or β due to vehicle translation, due to a change in direction of flight.

Reference Equations

Any Arbitrary Motion :

For Synthesis :	$F_i = f(\Sigma F_i, \alpha, \beta, \omega)$	ω = Rotation Rate (Ω, P, Q, R)
For WT Measurement :	$F_i = f(\alpha, \beta, \omega)$	F_i = Force or Moment
For Aero Database :	$C_i = f(F_i, \alpha, \beta, \omega)$	C_i = Force or Moment Coefficient
For Database Lookup:	$C_i = f(F_i, \alpha, \beta, \omega_{MOD})$	

Constant Rate Tests (Rotary Balance : Pure Rotational Motion about Velocity Vector)

For WT Measurement : A Least Squares approximation is used to sample, smooth, and average the **Rate** and **Force** data

$$\Delta C_i = C_i * \left| \Omega_{MOD} / \Omega \right| * (\Omega * \text{sign}(\Omega_{MOD})) * (b / 2V)$$

, where C_i is the **DV** term

Oscillatory Tests (Forced Oscillation and Plunge-Motion : Cyclical Motion about Body Axis or along Wind Axis)

For WT Measurement : A discrete Fourier approximation is used to sample, smooth, and average the **Rate** and **Force** data

Displacement at Time t $\quad S(t) = \Sigma X_k * e^{(-2\Pi * j * k * t)}$

Rotation Rate at Time t $\quad \omega(t) = \Sigma X_k * (-2\Pi * j * k) * e^{(-2\Pi * j * k * t)}$

Rate of Rotation Rate $\quad \omega'(t) = \Sigma X_k * (-2\Pi * j * k)^2 * e^{(-2\Pi * j * k * t)}$

For Database Lookup : Table entry is performed using (P_{MOD}, Q_{MOD}, R_{MOD}) or ($\dot{\alpha}_{TRANS}$, $\dot{\beta}_{TRANS}$) as the state parameters

$$\Delta C_i = \underbrace{[(C_{i\omega} * \Omega_\omega) * \left| \omega_{MOD} / \Omega \right| * (C_{i\omega} \dots]}_{\text{Sum of all contributing rotation terms}} * (b / 2V)$$

, where $C_{i\omega}$ is/are the **DV** term(s)

Software Program Description

The software program is essentially a simulation for generating and reducing data from a virtual wind tunnel. Both Static and Dynamic test conditions are considered.

The program will provide two important capabilities :

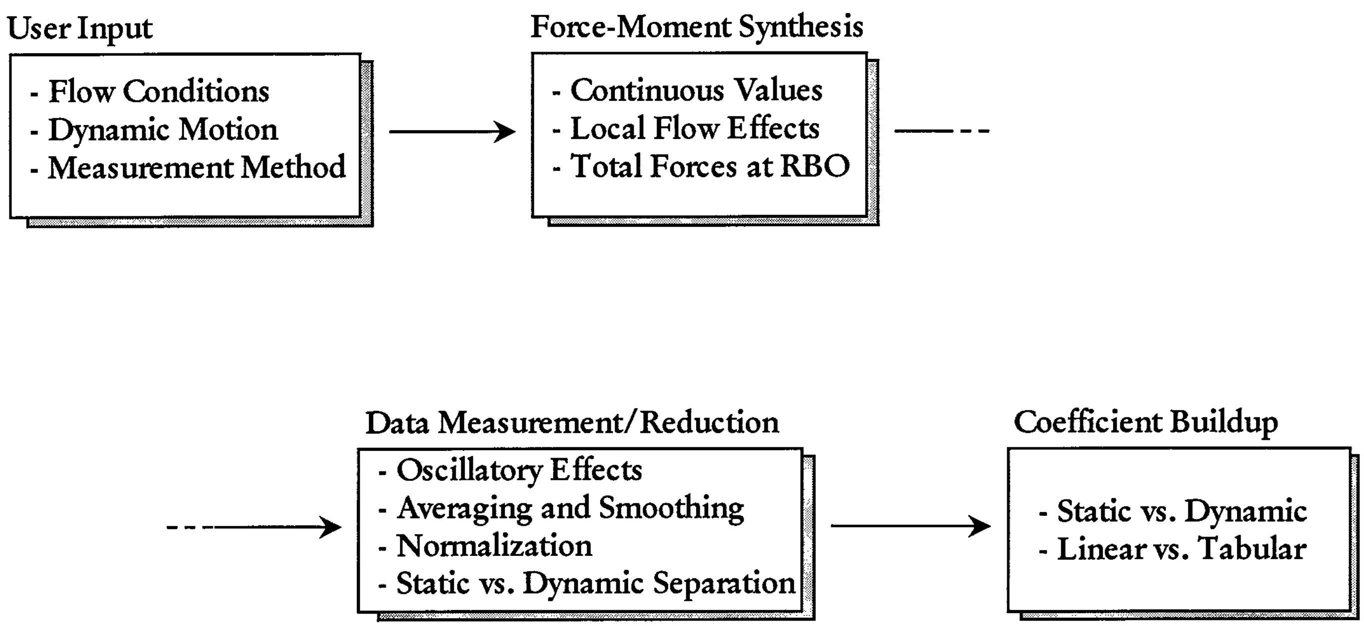
(1) Evaluation of the magnitude of aero coefficients to determine the relative importance of the various dynamic terms.

(2) Validation of the test measurement and reduction methods. This rehearsal will ensure that during an actual test the data is collected, formatted and reduced in a cost-efficient manner.

The Phase 1 SBIR prototype program will synthesize and reduce data for a typical modern tactical aircraft. A geometric model representative of an F16C will be used for the analysis. The F16 was chosen for its relative simplicity (conventional wing and empennage), and the availability of high AOA test data. Although the program is not intended to generate data that has a high degree of accuracy in an absolute sense, the magnitudes of values should approximate the actual aircraft.

The proposed Phase 2 SBIR production program will synthesize and reduce data for User-defined geometric models. Additionally, the program will import, reduce, and format actual wind-tunnel or water-tunnel test data. The program will provide an animation capability for viewing aircraft dynamic motion while displaying realtime time-history data of selected dynamic parameters. The resulting coefficient database will be suitable for linear analysis, simulation, or any of a number of post-processing analyses.

Software Architecture



Each module will provide tabular or graphical data output. This provides the User with insight into each incremental process during the generation of dynamic data.

The technical approach for developing each of the modules is presented on subsequent slides.

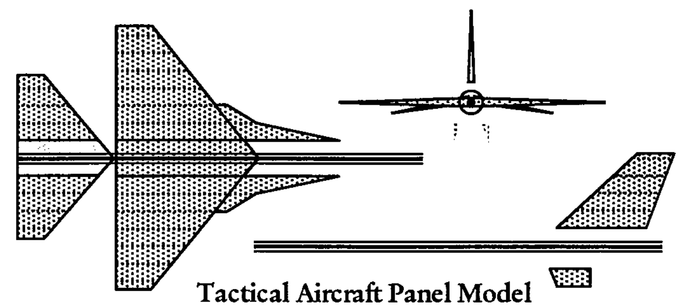
Software Technical Approach

User Input

- Flow Conditions
- Dynamic Motion
- Measurement Method

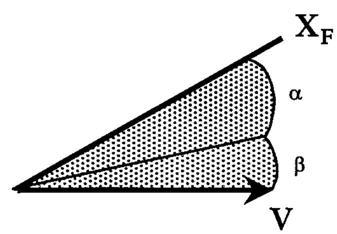
1 Air Vehicle Geometry Definition

- Lifting Surfaces: Chords-Span-Sweep-Twist-Dihedral
- Fuselage RBO
- Panel Dimensions and Moment Arms


Tactical Aircraft Panel Model

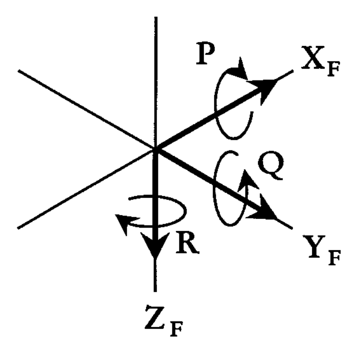
2 Body Flow Conditions

- Freestream Velocity, Density
- Fuselage AOA (α) and AOS (β)



3 Body Dynamic Motion

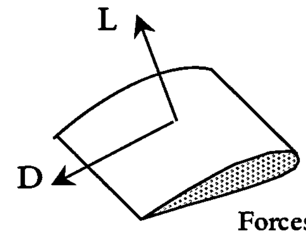
- Rotational Rates (P,Q,R)
- Translational Accelerations ($\dot{\alpha}$ and $\dot{\beta}$)
- Simulated Tunnel Test Motion



Software Technical Approach (cont.)

Force-Moment Synthesis

- Continuous Values
- Local Flow Effects
- Total Forces at RBO



Forces at Panel CP

$$F_X = -D \times \cos\alpha + L \times \sin\alpha$$
$$F_Z = -L \times \cos\alpha - D \times \sin\alpha$$

4 Flow Conditions at each Panel

- Local Axial & Tangential Velocities (U,V,W) ($V_{X\infty}$, $V_{Y\infty}$, $V_{Z\infty}$)
- Panel AOA (α) and AOS (β)
- Panel Lift (L) and Drag (D) at C.P. Coordinate (FS-BL-WL)
- Panel Forces (F_X , F_Z) at C.P. Coordinate (FS-BL-WL)

5 Aero Forces at RBO

- Coordinate Transform Panel-to-Fuselage
  (Sweep Λ - Dihedral Γ - Incidence i)
- Summation of Total Aero Forces and Moments

Forces at RBO

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix}_{ABC} = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix}_{PANEL}$$

$e_{11} = \cos i \cos\Lambda$
$e_{12} = \sin\Gamma \sin i \cos\Lambda - \cos\Gamma \sin\Lambda$
$e_{13} = \cos\Gamma \sin i \cos\Lambda + \sin\Gamma \sin\Lambda$

$e_{21} = \cos i \sin\Lambda$
$e_{22} = \sin\Gamma \sin i \sin\Lambda + \cos\Gamma \cos\Lambda$
$e_{23} = \cos\Gamma \sin i \sin\Lambda - \sin\Gamma \cos\Lambda$

$e_{31} = -\sin i$
$e_{32} = \sin\Gamma \cos i$
$e_{33} = \cos\Gamma \cos i$

Moments at RBO

$$M_X = L = ArmY \times F_Z - ArmZ \times F_Y$$
$$M_Y = M = ArmZ \times F_X - ArmX \times F_Z$$
$$M_Z = N = ArmX \times F_Y - ArmY \times F_X$$

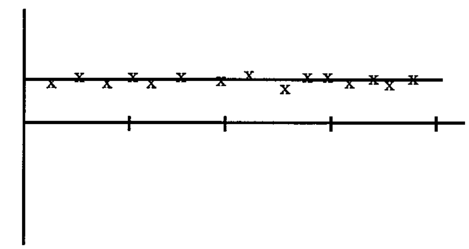
Software Technical Approach (cont.)

Data Measurement/Reduction

- Oscillatory Effects
- Averaging and Smoothing
- Normalization
- Static vs. Dynamic Separation

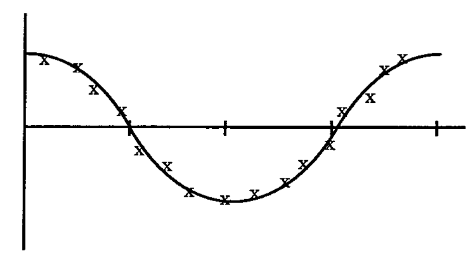
6 Static and Non-Oscillatory Data

- Baseline Coefficient (Static Term) at Body AOA (α) and AOS (β)
- Rotary-Balance (Constant Rate) at Body AOA (α) and AOS (β)
- Linear Regression Methods applied for sampling/smoothing/averaging
- Conversion to Coefficient Form; Baseline vs. Incremental Term Separation



7 Oscillatory Data

- Forced-Oscillation Motion at varying Frequency-Amplitude combinations
- Plunge-Oscillation Motion at varying Frequency-Amplitude combinations
- Fourier Curvefit Methods applied for sampling/smoothing/averaging
- Conversion to Coefficient Form; Baseline vs. Incremental Term Separation



Software Technical Approach (cont.)

Coefficient Buildup

- Static vs. Dynamic
- Linear vs. Tabular

8 Aero Coefficient Database Format

- Store all non-linear (tabular) data as $DV = f(IV_1, IV_2, ...)$
- Store Static Coefficients as Baseline DV Term
- Store Dynamic Coefficients as non-linear Incremental DV Terms

$$C_{BASE} = f(IV_1, IV_2, ...) = f(\alpha, \beta)$$
$$\Delta C_P = f(IV_1, IV_2, ...) = f(P, \alpha, \beta)$$
$$\Delta C_i = f(IV_1, IV_2, ...) ...$$

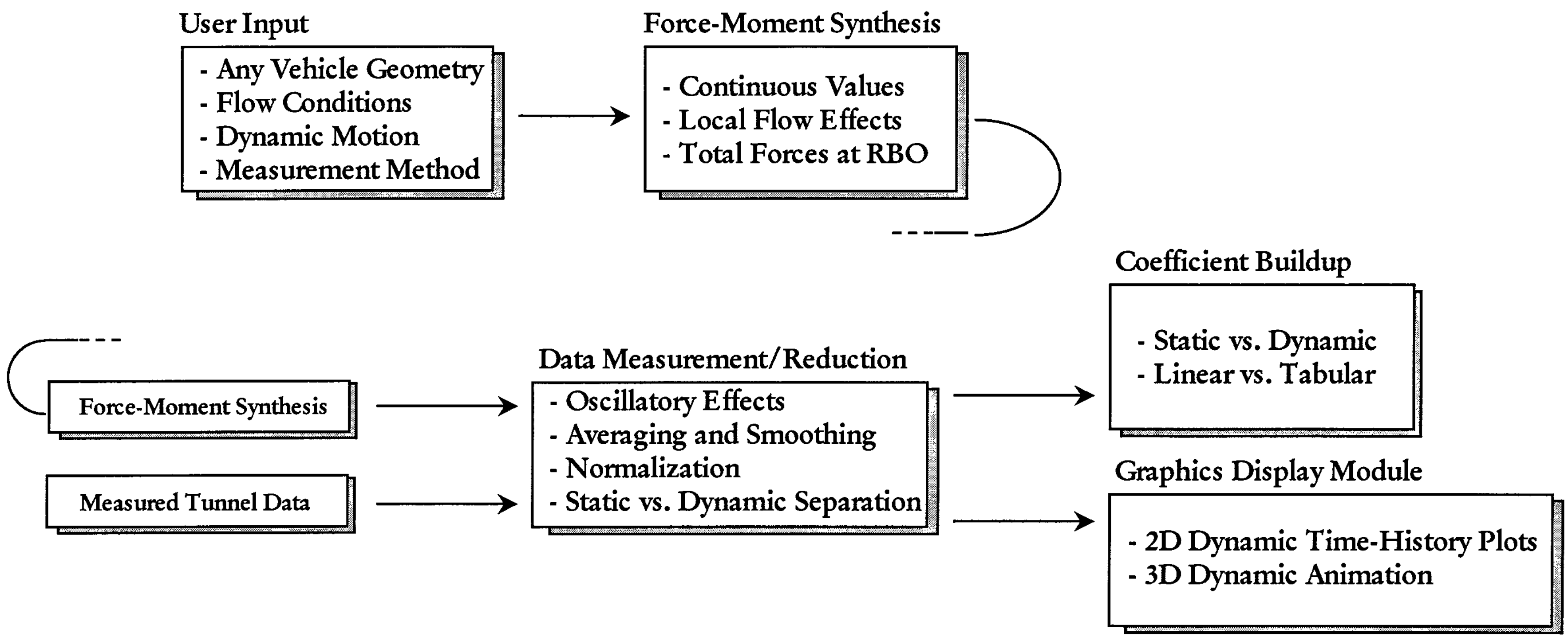
9 Aero Coefficient Buildup

- Baseline Coefficient (Static Term) at Body AOA (α) and AOS (β)
- Incremental Coefficients $f(P, \alpha, \beta)$, $f(Q, \alpha, \beta)$, $f(R, \alpha, \beta)$, $f(\Omega, \alpha, \beta)$
- Database Entry/Interpolation with (P_{MOD}, Q_{MOD}, R_{MOD}, Ω_{MOD}) as state variables
- Incremental Coefficients $f(\dot{\alpha}_{TRANS}, \alpha, \beta)$, $f(\dot{\beta}_{TRANS}, \alpha, \beta)$
- Database Entry/Interpolation with ($\dot{\alpha}_{TRANS}$, $\dot{\beta}_{TRANS}$) as state variables

$$C_i = C_{BASE} + \Delta C_i(P) + \Delta C_i(\Omega) ...$$

Software Architecture

SBIR Phase 2 Description



Each module will provide tabular or graphical data output. This provides the User with insight into each incremental process during the generation/analysis of dynamic data.

Progress Report # 3

Progress Report
CLIN 0002
Data Item A001

Improved Wind Tunnel Data Reduction Procedure
SBIR N96-019

Contract No. N00019-96-C-2025
Firm Fixed Price $74,365.19
Competitively Awarded

Sponsor
Robert Hanley
Naval Air Systems Command
1421 Jefferson Davis Hwy
Arlington, VA 22243

Contractor
Sight, Sound and Motion Corp.
325 East Hillcrest Dr. # 100
Thousand Oaks, CA 91360-5828

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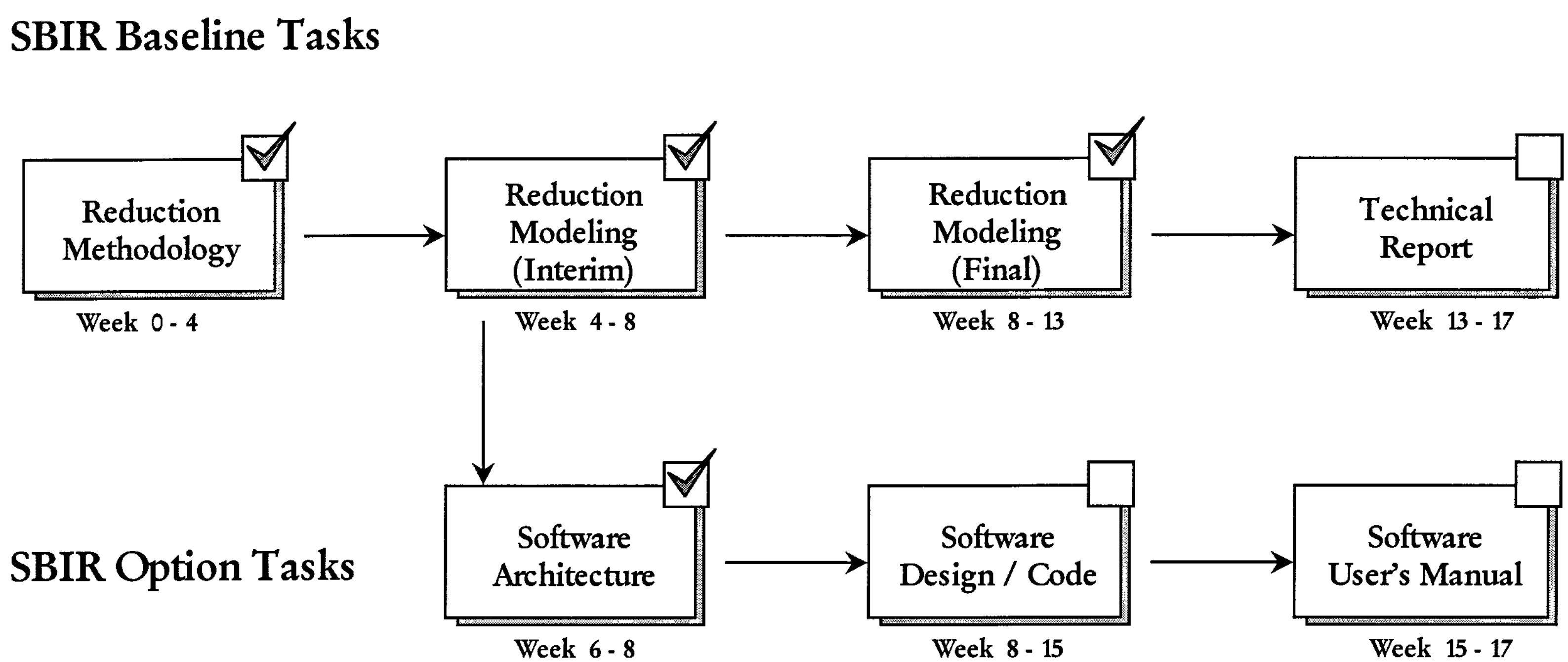
- ❑ SBIR Task Overview and Progress
- ❑ Reduction Method Technical Description
- ❑ Reduction Method Test Cases
- ❑ Software Program Status
- ❑ Sample Software User Interface

SBIR Task Overview and Progress

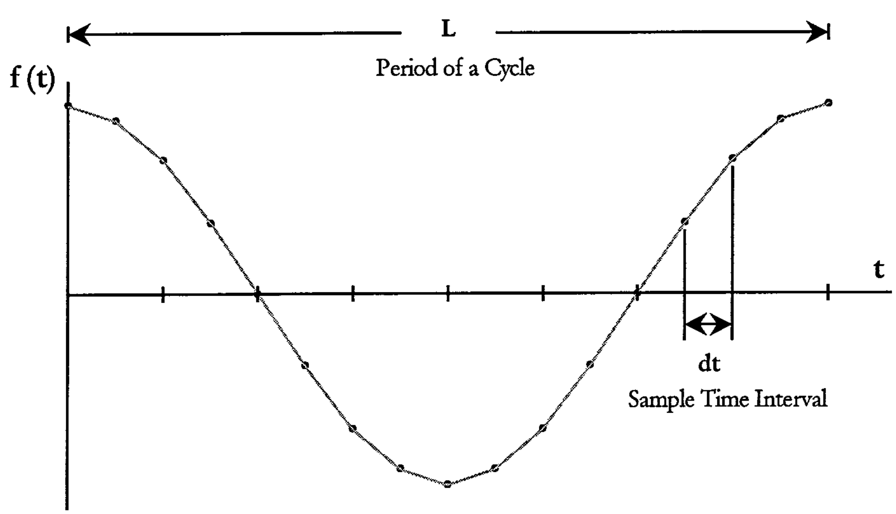


Reduction Method Technical Description

Oscillatory Test Measurement (Forced Oscillation and Plunge-Motion)

Since these motions are cyclic in nature, a Fourier analysis method can be applied to the measured data to provide natural smoothing, averaging, and aerodynamic coefficient extraction. The advantage of a Fourier approximation is its ability to control frequency content and measurement error by appropriate selection of the sample interval (dt) and the number of sampled cycles (k).

Once the Fourier coefficients have been determined from measured data, derivatives of the equations provide aerodynamic coefficients as a function of rate. As an example, a forced-oscillation test about body X-axis would provide $C_l(p)$ ... Rolling Moment (C_l) as a function of Roll Rate (p) .



If $m = k * i$ for $i = 0, 1, 2, \ldots (N-1)$ then,

$$G(m) = F(i) + (1/(k*N))\ sum(n=0 \text{ to } n=k*N-1) * \{e(n)\ exp(2\pi * j * i * n / N)\}$$

$G(m)$	m*th* Fourier coefficient of **k** cycles
$F(i)$	i*th* Fourier coefficient of $f(t)$
$e(n)$	Error in the m*th* measurement
N	Number of Samples/Cycle
k	Number of Cycles
n	n*th* Sample in a Cycle
j	sqrt(-1)

Reduction Method Test Cases

Both the motion of the vehicle and the sampling of measured forces are modeled using a Fourier approximation.

Actual measured data have errors due to bias, noise, etc. Bias error affects the constant term in a Fourier series, which also represents the static aerodynamic effects. The higher-order Fourier terms contain the dynamic data content, and when treated as an incremental coefficient term, will not be affected by bias error. Noise error can be minimized by sampling at sufficient density over several cycles.

The number of Samples/Cycle (N) should be selected to match the frequency of the problem. If the notional vehicle force dynamics have expected frequency content less than 50 Hz, then an N of 128 would result in a low-pass cutoff of 64 Hz.

Similarly, the minimum number of Cycles/Run (k) should be selected to minimize noise error. For an expected measurement noise M and desired worst-case error of e, then the formula for k is,

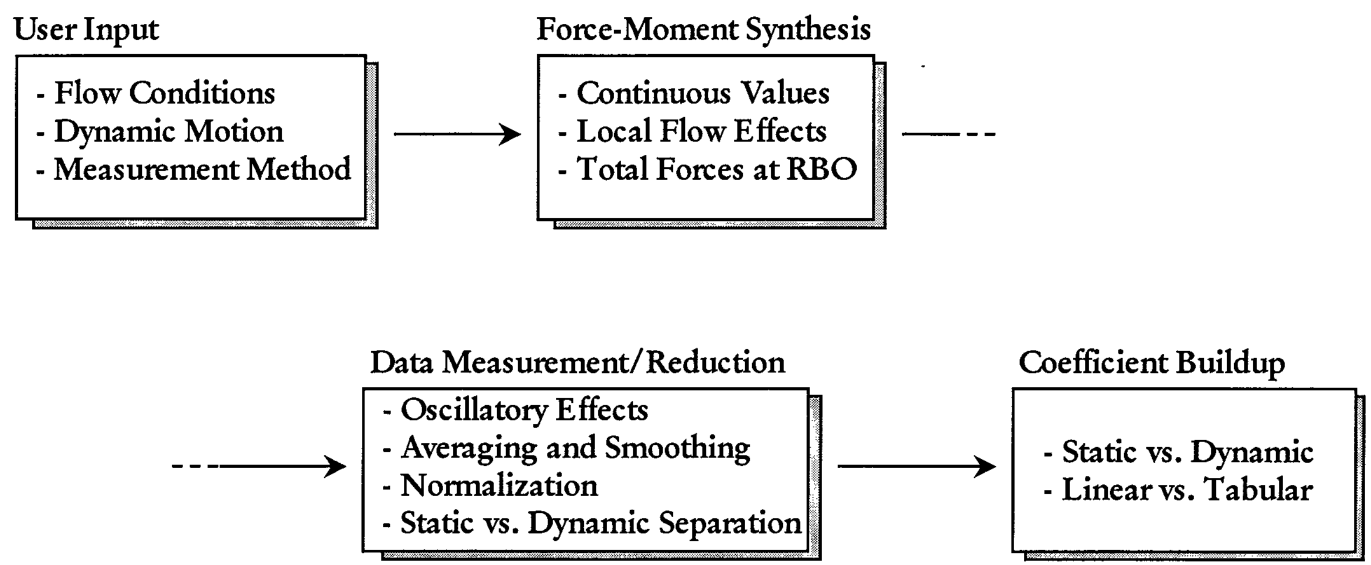
$$k = M / (N * e)$$

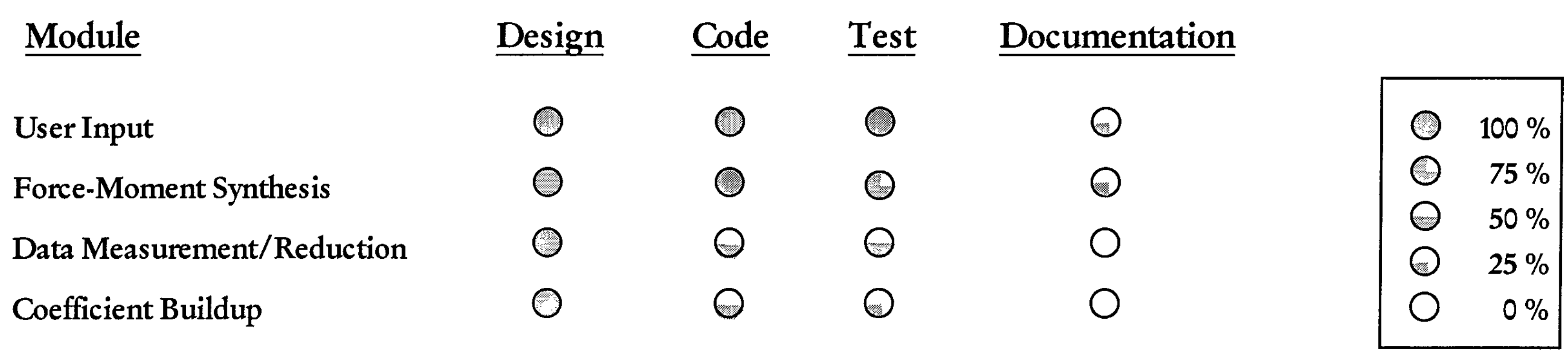
Error analysis data are provided for random-generated noise inputs of sinusoidal waveform. The signal-to-noise ratio was set at 1:1, to test an extreme error condition.

The data indicate that the error is linear with the maximum amplitude of the noise M, hence as the S/N ratio increases by a factor of 10 the error is reduced by a factor of 10.

N Number of Samples/Cycle	k Number of Cycles	Maximum Error
8	1	.07991
32	1	.15515
128	1	.001159
512	1	.01748
8	8	.04240
32	8	.00794
128	8	.01206
512	8	.00676
8	512	.01252
32	512	.00180
128	512	.00197
512	512	.00085

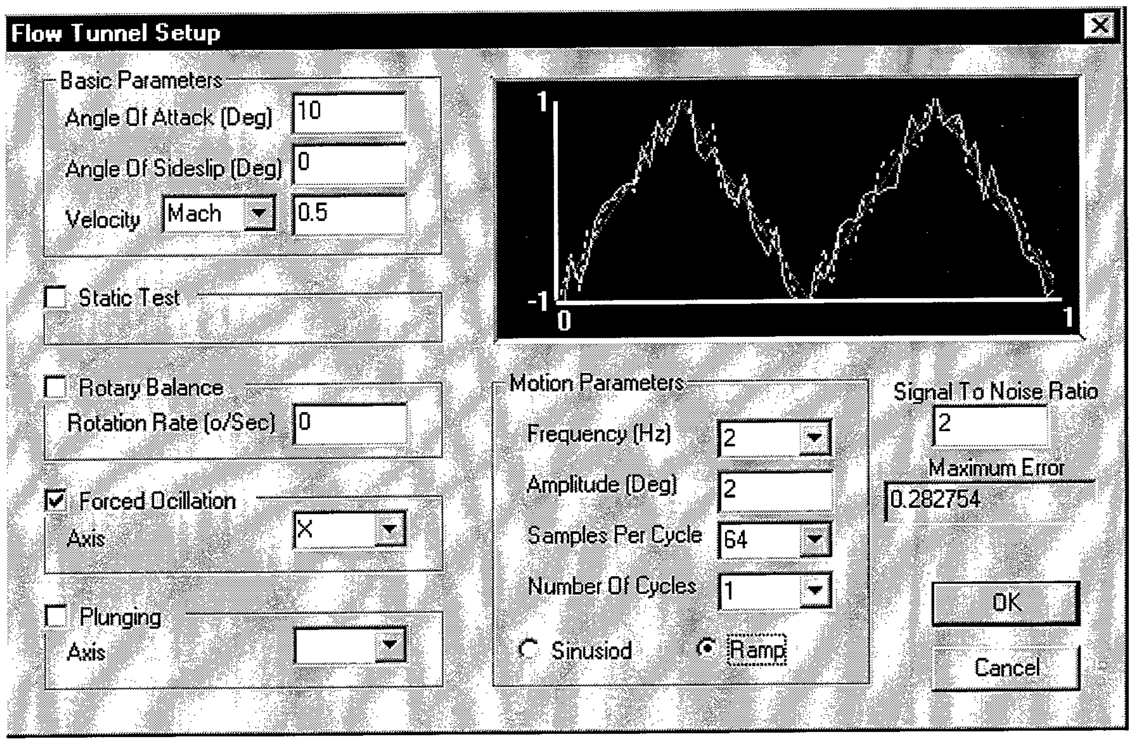
Software Program Status





Sample Software User Interface

Each module of the *AeroMaster* software program will present the User with a graphic-user-interface (GUI) as the mechanism for data entry and data visualization. Since GUI's are the visual element of a good man-machine-interface, Users are encouraged to provide feedback on human factors such as intuitiveness, correctness, and completeness.



Shown here is the prototype GUI for entry of tunnel test and flow condition data. It provides the **Force-Moment Synthesis** module with input parameters for generation of non-linear aero data. The color plot shows the input waveform for oscillatory tests, overlaid with expected goodness-of-fit for the Fourier approximation given S/N ratio, Cycles, and Samples/Cycle.