4-30-2019

Donahue Spring 2019 Independent Study; Collection of Aerodynamic Stability and Control Lecutre Notes

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Spring 2019

Aerodynamic Stability & Control

MEMS 500: Independent Study

Donahue, Daniel

Daniel Donahue's Independent Study

The learning objective of this independent study was to further my own knowledge in the field of Flight Mechanics/Dynamics as well as attaining experience in creating coursework. This was done by creating 10 lectures worth of hand-written notes on the subject of Aircraft Stability and Control, creating a written syllabus that outlines this work done during Spring 2019 as wells as the work done during Fall 2018 (following page), and five questions that cover the discussed topics that could be used on homework or exams. I primarily used the book by Pamadi, "Performance, Stability, Dynamics, and Control of Airplanes 2nd ed" while also pulling from my experiences as an aerodynamic stability and control engineer.

During the course of the semester I generated 30 pages of hand written notes that correspond to 10 lectures worth of material. It was agreed upon with my advisor, David Peters, that 3 pages of hand written notes would equate to a lecture. This number was based off of his experience with lecture materials where 3 pages of hand written notes, accompanied by in-person elaboration of the material, equates to one lecture worth of material.

Below is a syllabus of the 10 covered lectures with corresponding pages in the hand-written notes attached.

Lecture	**Topic**	**Note Pages**
1	Nomenclature and Euler Angle conversions	1-2
2	Kinematic and Inertial Coupling with Spin Mode discussions	3-5
3	Aero Database Summations and Downwash Angle	6-9
4	Engine Forces and Moments	10-11
5-8	Wind Tunnel Testing	12-26
9-10	Flight Testing	27-30

Mechanical Engineering & Materials Science
Aerodynamic Stability and Control

Instructor: Daniel Donahue

Course Summary:

This course provides an introduction to aerodynamic stability and control fundamentals. The course covers basic aircraft nomenclature, a full nonlinear derivation of aircraft equations of motion, aircraft stability and dynamic derivatives, and aircraft performance. Course special topics include discussion of different types of wind tunnel testing, flight testing and insight into how a practicing engineer verifies data fidelity.

Major Topics:

1. Aircraft Geometry, Nomenclature and Axes Systems
2. Aircraft Equations of Motion
3. Longitudinal Characteristics
4. Maneuvering Performance
5. Lateral-Directional Characteristics
6. Dynamic Derivatives and Spin Characteristics
7. Hinge Moments
8. Engine Forces and Moments
9. Wind Tunnel Testing
10. Flight Testing

Question Bank:

1) Show that both equations are to determine a heading angle, but the second is quadrant independent:

$\tan^{-1}\frac{y}{x}$ $\qquad$ $2\tan^{-1}\frac{\sqrt{x^2+y^2}-x}{y}$

2) Derive the kinematic coupling terms from the aircraft equations of motion. What yaw rate is required to coordinate no sideslip generation for $100°/s$ of roll rate at 0° AOA? 15° AOA? 35° AOA?

3) After returning from a Free Spin test, you are provided with the following wind tunnel data:

- x, y, z, model positions in the tunnel during testing
- V_{sink}, the tunnel operating speed
- ψ, θ, ϕ, model Euler Angles
- All mass properties for the model

Calculate the six aerodynamic coefficients ($C_L, C_m, C_D, C_l, C_n, C_Y$).

4) Given the below pitching moment data, calculate the tail required to trim the aircraft and the downwash angle on the tail.

	Horizontal Tail Position											
Angle of Attack	-30	-25	-20	-15	-10	-5	0	5	10	15	20	Off
-16	0.54	0.49	0.44	0.39	0.34	0.29	0.24	0.19	0.14	0.09	0.04	0.07
-12	0.48	0.43	0.38	0.33	0.28	0.23	0.18	0.13	0.08	0.03	-0.02	0.065
-8	0.42	0.37	0.32	0.27	0.22	0.17	0.12	0.07	0.02	-0.03	-0.08	0.06
-4	0.39	0.34	0.29	0.24	0.19	0.14	0.09	0.04	-0.01	-0.06	-0.11	0.058
0	0.36	0.31	0.26	0.21	0.16	0.11	0.06	0.01	-0.04	-0.09	-0.14	0.06
4	0.315	0.265	0.215	0.165	0.115	0.065	0.015	-0.035	-0.085	-0.135	-0.185	0.062
8	0.279	0.229	0.179	0.129	0.079	0.029	-0.021	-0.071	-0.121	-0.171	-0.221	0.063
12	0.248	0.198	0.148	0.098	0.048	-0.002	-0.052	-0.102	-0.152	-0.202	-0.252	0.102
16	0.215	0.165	0.115	0.065	0.015	-0.035	-0.085	-0.135	-0.185	-0.235	-0.285	0.14
20	0.21	0.16	0.11	0.06	0.01	-0.04	-0.09	-0.14	-0.19	-0.24	-0.29	0.1125
24	0.167	0.117	0.067	0.017	-0.033	-0.083	-0.133	-0.183	-0.233	-0.283	-0.333	0.073
28	0.14	0.09	0.04	-0.01	-0.06	-0.11	-0.16	-0.21	-0.26	-0.31	-0.36	0.06
32	0.075	0.025	-0.025	-0.075	-0.125	-0.175	-0.225	-0.275	-0.325	-0.375	-0.425	0.04

5) Show why implementing the rolling moment damping term in an aerodynamic database should not use the following logic. Provide two ways to use the same data set, but have correct implementation.

$$\Delta C_{l_{\frac{\Omega b}{2V_T}}} = f\left(\alpha, M, |\beta|, \frac{\Omega b}{2V_T}\right) * sign(\beta)$$

04/06/19

NOMENCLATURE

AIRCRAFT ANGLES RELATIVE TO THE AIR MASS

→ RELATE AIRCRAFT COORDINATES TO FLIGHT PATH COORDINATES

α ANGLE OF ATTACK → ANGLE BETWEEN THE AIRCRAFT BODY X AXIS AND THE PROJECTION OF THE VELOCITY VECTOR RELATIVE TO THE AIR MASS ON THE BODY ~~AXIS~~ X–Z PLANE. POSITIVE UP ROTATION.

β SIDESLIP ANGLE → ANGLE BETWEEN THE VELOCITY VECTOR RELATIVE TO THE AIR MASS AND THE AIRCRAFT BODY X-Z PLANE. POSOTIVE IS "WIND IN THE RIGHT EAR"

EULER ANGLES

ψ AIRCRAFT HEADING ANGLE → HORIZONTAL ANGLE BETWEEN SOME REFERENCE DIRECTION (USUALLY NORTH) & THE PROJECTION OF THE AIRCRAFT BODY X AXIS ON THE HORIZONTAL PLANE. POSITIVE IS NORTH TO EAST.

θ AIRCRAFT PITCH ANGLE → VERTICAL ANGLE BETWEEN THE HORIZONTAL PLANE & THE AIRCRAFT BODY X AXIS. POSITIVE IS ROTATION UP.

ϕ AIRCRAFT ROLL ANGLE → ANGLE BETWEEN THE VERTICAL PLANE CONTAINING THE AIRCRAFT X AXIS & THE AIRCRAFT BODY X-Z PLANE. POSITIVE IS CLOCKWISE ABOUT THE BODY X AXIS WHEN LOOKING FORWARD (RIGHT WING DOWN)

ROTATIONAL RATES

p BODY AXIS ROLL RATE, POSITIVE RIGHT WING DOWN.

q BODY AXIS PITCH RATE, POSITIVE NOSE UP.

r BODY AXIS YAW RATE, POSITIVE NOSE RIGHT.

RELATIONSHIP BETWEEN BODY AXIS ROTATIONAL RATES & EULER ANGLES

$$p = \dot{\phi} - \dot{\psi} \sin\theta$$

$$q = \dot{\theta}\cos\phi + \dot{\psi}\cos\theta\sin\phi$$

$$r = \dot{\psi}\cos\theta\cos\phi - \dot{\theta}\sin\phi$$

$\Rightarrow$

$$\dot{\phi} = p + (q\sin\phi + r\cos\phi)\tan\theta$$

$$\dot{\theta} = q\cos\phi - r\sin\phi$$

$$\dot{\psi} = (q\sin\phi + r\cos\phi)/\cos\theta$$

$\rightarrow$ INDETERMINATE WHEN $\theta = \pm 90°$

WIND MAGNITUDE & DIRECTION

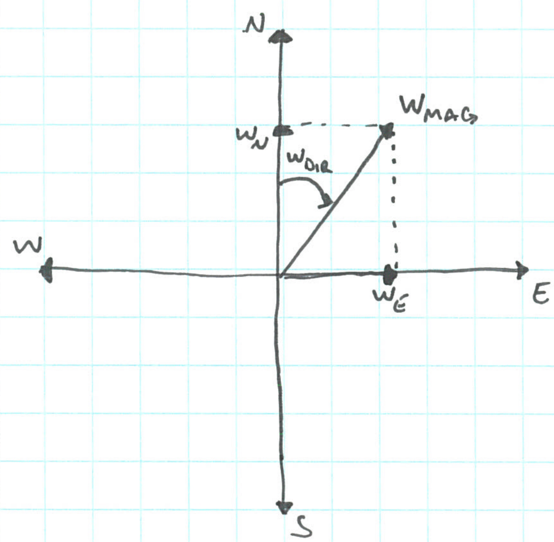
$W_N \rightarrow$ NORTH WIND

$W_E \rightarrow$ EAST WIND

$W_D \rightarrow$ DOWN WIND

$W_{MAG} \rightarrow$ WIND MAGNITUDE

$W_{DIR} \rightarrow$ WIND DIRECTION



$$W_{MAG} = \sqrt{W_N^2 + W_E^2 + W_D^2}$$

$$W_{DIR} = 2\tan^{-1}\left[\frac{\sqrt{W_N^2 + W_E^2} - W_N}{W_E}\right]$$

04/06/19

KINEMATIC COUPLING

EQUATIONS OF MOTION TERMS THAT CHARACTERIZE THE EFFECT OF ROLL, PITCH & YAW RATE ~~ON~~ ANGLE OF ATTACK & SIDESLIP GENERATION.

BEGIN WITH THE RATE-DEPENDENT $\dot{\alpha}$ & $\dot{\beta}$ TERMS

$$\dot{\beta} = P \sin\alpha - R\cos\alpha$$

~~SUBSTITUTE~~

$$\dot{\alpha} = q + \frac{1}{\cos\alpha\cos\beta}\left(-P\sin\beta + \dot{\beta}\sin\beta\sin\alpha\right) = \cancel{q - \tan\beta\,(P\cos\alpha + R\sin\alpha)}$$

SUB-IN $\dot{\beta}$ INTO $\dot{\alpha}$

$$\rightarrow \dot{\alpha} = q - \tan\beta\,(P\cos\alpha + R\sin\alpha)$$

THE ABOVE $\dot{\alpha}$ & $\dot{\beta}$ TERMS ARE THE KINEMATIC COUPLING TERMS. THEY EMPHASIZE WHY COORDINATED ROLLS ARE EXTREMELY IMPORTANT AT HIGH ANGLES OF ATTACK. COORDINATED ROLLS ARE WHEN ROLL & YAW RATE ARE BALANCED TO REDUCE $\dot{\alpha}$ & $\dot{\beta}$.

EXAMPLE

A SIMPLE BODY AXIS ROLL OF 100°/S COMMANDED AT 30° ANGLE OF ATTACK WILL GENERATE 50°/S SIDESLIP RATE IF NO COORDINATING YAW IS INPUT.

A COORDINATED ROLL IS A "ROLL ABOUT THE VELOCITY VECTOR" & REQUIRES A BALANCE IN ROLL & YAW RATE TO ACHIEVE.

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INERTIAL COUPLING

~~THIS~~ EQUATIONS OF MOTION TERMS THAT CHARACTERIZE THE EFFECT OF ROLL, PITCH, & YAW RATE ON ROLL, PITCH, & YAW ACCELERATIONS.

CROSS-AXIS ~~COMPONENTS~~ MOMENTS OF INERTIA & PRODUCTS OF INERTIA CAN DRIVE RATES DURING MANEUVERING FLIGHT.

$$I_{xx}\dot{p} = (I_{YY} - I_{ZZ})qr + I_{xz}(\dot{r} + pq)$$

$$I_{YY}\dot{q} = (I_{ZZ} - I_{XX})pr + I_{xz}(r^2 - p^2)$$

$$I_{ZZ}\dot{r} = (I_{XX} - I_{YY})pq + I_{xz}(\dot{p} - qr)$$

THE ABOVE EXCLUDES THE AERODYNAMIC COMPONENTS JUST TO SHOW THE EFFECTS OF INERTIAL COUPLING.

AN EXAMPLE CAN BE THOUGHT THROUGH FOR THE CASE WHERE AN AIRCRAFT PERFORMS A 1g ROLL. IN THIS CASE, PLENTY OF ROLL RATE (p) IS GENERATED. IF ~~SIMULTANEOUS~~ INSTANTANEOUS YAW RATE WERE APPLIED (r), THEN THE AIRCRAFT WOULD EXPERIENCE A LARGE AMOUNT OF PITCH RATE GENERATION THROUGH

$$\dot{q} = \frac{I_{ZZ} - I_{XX}}{I_{YY}} pr$$

THIS IN TURN CAN DEVELOP THE OTHER RATES THROUGH THE INCLUSION OF PITCH RATE (q) AND DRIVE THE SYSTEM UNSTABLE & TOWARDS DEPARTURES FROM COMMANDED FLIGHT.

04/06/19

STEADY-STATE SPIN MODES

IN THE CASES OF STEADY-STATE SPINS, THE INERTIAL & AERODYNAMIC MOMENTS ARE BALANCED TO HAVE

$$\dot{p} = \dot{q} = \dot{r} = \emptyset$$

THUS THE EQUATIONS OF MOTION CAN BE RE-WRITTEN IN A FORM TO ANALYZE THESE CASES:

$$\text{AERO} = \text{INERTIAL}$$

$$\bar{q} S b C_l = I_{zz} q r - I_{yy} q r - I_{xz} p q$$

$$\bar{q} S c C_m = I_{xx} p r - I_{zz} p r + I_{xz} (p^2 - r^2)$$

$$\bar{q} S b C_n = I_{yy} p q - I_{xx} p q + I_{xz} q r$$

INERTIAL TERMS & STATE VARIABLES CAN BE SET (M, h, etc) TO ASSESS THE FEASABILITY OF A STEADY-STATE SPIN MODE.

HOWEVER, KEEP IN MIND THAT THE AERODYNAMIC COEFFICIENTS ARE DEPENDENT UPON NOT ONLY STATE VARIABLES, BUT ALSO THE ROTATION RATES THROUGH THE ~~DAMPING PER~~ DYNAMIC DERIVATIVE TERMS.

FURTHER COMPLICATING SPIN ANALYSIS IS THE KINEMATIC COUPLING TERMS THAT MAY ALSO DRIVE THE STATE VARIABLES & THEREFORE MODIFY THE AERODYNAMIC CHARACTERISTICS FURTHER.

ALSO, ENGINE GYROSCOPIC EFFECTS COULD BE CONSIDERED FOR A MORE COMPREHENSIVE ANALYSIS.

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AERODYNAMIC COMPONENT SUMMATION

LONGITUDINAL & LATERAL-DIRECTIONAL TERMS ARE A SUMMATION OF INDIVIDUAL AERODYNAMIC CONTRIBUTIONS:

IE $C_m = C_{m_0}(\alpha, M, h)$ → BASIC PITCHING MOMENT

$+ \Delta C_{m_\beta}(\alpha, M, \beta, h)$ → SIDESLIP EFFECT ON PITCHING MOMENT

$+ \Delta C_{m_{\delta H}}(\alpha, M, \delta H)$ → HORIZONTAL STABILATOR EFFECT ON PITCHING MOMENT

$+ \Delta C_{m_{\frac{\Omega b}{2V}}}(\alpha, M, \frac{\Omega b}{2V})$ → STEADY STATE ROTATION EFFECT ON PITCHING MOMENT

$+ \Delta C_{m_{\frac{q\bar{c}}{2V}}}(\alpha, M, \frac{q\bar{c}}{2V})$ → OSCILLATORY PITCH RATE EFFECT ON PITCHING MOMENT

$+ \ldots$ ETC.

$C_l = C_{l_0}(\alpha, M)$ → BASIC ROLLING MOMENT
→ COULD BE ASSUMED TO BE ZERO

$+ \Delta C_{l_\beta}(\alpha, M, \beta)$ → INCREMENTAL EFFECT OF SIDESLIP ON ROLLING MOMENT

$+ \Delta C_{l_{\delta T}}(\alpha, M, \delta T)$ → INC. EFFECT OF DIFFERENTIAL TAIL ON ROLLING MOMENT

→ COULD BE IMPLEMENTED AS $+\Delta C_{l_{\delta H_L}} - \Delta C_{l_{\delta H_R}}$

$+ \Delta C_{l_{\delta H, \delta R}}(\alpha, M, \delta H, \delta R)$ → INCREMENTAL EFFECT OF RUDDER / STABILATOR INTERACTION

$+ \Delta C_{l_{\delta H, \delta R, \beta}}(\alpha, M, \delta_H, \delta_R, \beta)$ → DITTO, BUT ALSO SIDESLIP

IDEA IS TO HAVE INDIVIDUAL COMPONENTS SUM UP THROUGH ~~THE~~ TO GET A TOTAL COEFFICIENT.

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AERODYNAMIC DATA CAN BE COLLECTED FROM SEVERAL SOURCES OF VARYING FIDELITY:

INCREASING FIDELITY

EMPERICAL EQUATIONS

VORTEX LATTICE / PANEL METHOD CODE

} COVERED IN EARLIER AERO COURSES

COMPUTATIONAL FLUID DYNAMICS } TAKE CFD OR USE AN APPLICATION

WIND TUNNEL TESTING

FLIGHT TESTING

} WILL BE COVERED HERE TO SOME EXTENT

WITH INCREASED FIDELITY COMES INCREASED COST. EACH OF THESE SOURCES SHOULD COME INTO AN AERODYNAMIC MODEL IF THE PROGRAM LIVES LONG ENOUGH

EMPIRICAL EQUATIONS & SOURCE PANEL METHOD CODES TYPICALLY PROVIDE EARLY FEASABILITY STUDIES TO SEE IF AN AIRCRAFT CONFIGURATION COULD POTENTIALLY MEET REQUIREMENTS

CONFIGURATIONS ARE FURTHER REFINED (NOWADAYS) WITH COMPUTATIONAL FLUID DYNAMICS. TODAY'S METHODS UTALIZE FULL THREE DIMENSIONAL MODELS WITH INPUT FROM ALL DISCIPLINES. HERE AERO & PROPULSION CAN ALSO BE MODELED TOGETHER. HOWEVER EVEN TODAY'S CFD METHODS DON'T ALWAYS PROVIDE REASONABLE ANSWERS IN CERTAIN REGIONS OF THE ENVELOPE, (HIGH AOA). WHERE LARGE SEPARATION OCCURS

WIND TUNNEL TESTING IS CONSIDERED HIGHER FIDELITY THAN CFD. ~~TH~~ DURING THIS STEP, TO-SCALE MODELS ARE CREATED & TESTED IN FLOW FIELDS.

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THESE TO-SCALE MODELS SURROUND A BALANCE THAT CAN MEASURE THE DIFFERENT FORCES & MOMENTS THAT THE MODEL IS GENERATING. AN ADDED BENEFIT OF WIND TUNNEL TESTING IS THE ABILITY TO QUICKLY COLLECT DATA POINTS ONCE THE MODEL IS INSTALLED IN THE FACILITY. SOME CFD SOLUTIONS CAN TAKE UP TO SEVERAL DAYS TO WEEKS TO COME TO AN ANSWER ~~WHERE~~ FOR A SINGLE POINT. IN CONTRAST, AN ENTIRE SWEEP FROM -90° TO +90° ANGLE OF ATTACK CAN BE COLLECTED IN MERE HOURS DURING A WIND TUNNEL TEST.

A WIND TUNNEL TEST ALSO ALLOWS THE ENGINEER TO HAVE COMPLETE CONTROL OVER THE STATE VARIABLES BEING TESTED AS WELL AS THE CONFIGURATION. CONTROL SURFACE DEFLECTIONS CAN BE SPECIFICALLY SET IN A WIND TUNNEL WHERAS IN FLIGHT TESTING THE CONTROL SYSTEM IS DRIVING THE SURFACES.

ALL OF THIS SAID, FLIGHT TESTING IS CONSIDERED THE FINAL ANSWER. MEASUREMANT INSTRUMENTATION CAN BE MODIFIED INTO AN AIRCRAFT TO COLLECT FLIGHT TEST DATA AND EXTRACT THE AERODYNAMIC COEFFICIENTS. DEPENDING ON THE LEVEL OF UNCERTAINTY IN THE INSTRUMENTATION & COLLECTED DATA, THE AERO COEFFICIENTS CAN BE EXTRACTED WITH A CERTAIN LEVEL OF CONFIDENCE.

FLIGHT TEST DATA IS COMPARED TO WIND TUNNEL & CFD TO HELP "PAINT A PICTURE" OF WHERE EACH MODEL SAYS THE COEFFICIENTS SHOULD BE. IDEALLY, AN ENGINEER WOULD BE ABLE TO GO TO FLIGHT WITH ~~THE ARE A REASONAB~~ A PERFECT AERO MODEL, BUT FURTHUR CFD & WIND TUNNEL TESTING FIDELITY MAY BE REQUIRED. THE PROCESS OF EXTRACTING THE AERO COEFFICIENTS FROM FLIGHT TEST DATA IS REFERRED TO AS PARAMETER IDENTIFICATION (PID).

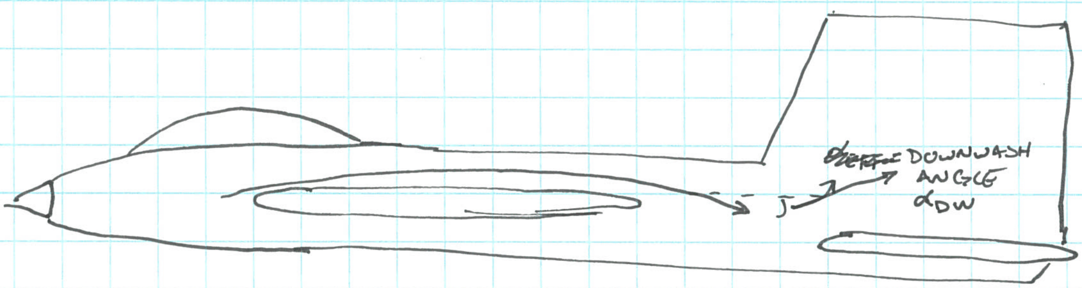
04/06/19

DOWNWASH ANGLE

~~ANGLE IN~~

EFFECTIVE ANGLE ON HORIZONTAL STABILIZER THAT INCLUDES THE EFFECT OF THE WING ON THE AIR STREAM IMPINGING ON THE CONTROL SURFACE.

SOMETIMES THIS ANGLE IS USED ~~AS THE~~ IN LIEU OF ANGLE OF ATTACK FOR HORIZONTAL STABALIZER ANALYSIS. AERODYNAMIC & HINGE MOMENT MODELS MAY BE BUILT WITH THIS DOWNWASH ANGLE IN MIND.



THUS: $\alpha_{EFF} = \alpha - \alpha_{DW} \rightarrow \alpha_{TAIL} = \alpha_{TRUE} + \delta_H - \alpha_{DW}$

OTHER WING CONTROL SURFACESS CAN ~~PLAY~~ EFFECT THE DOWNWASH ANGLE. IF THE AILERONS OR FLAPS ARE EXTENDED, THEY WILL EFFECT THE FLOW ~~THAT~~ ACTS ON THE HORIZONTAL TAIL.

NOTE THAT THIS DOWNWASH ANGLE VARRIES WITH ANGLE OF ATTACK & IT IS SOMETIMES (MUST TIMES IN MY PRACTICE) TO JUST MODEL AERO INCREMENTS FROM THE TAIL AS A FUNCTION OF TRUE AIRCRAFT ANGLE OF ATTACK.

04/06/19

ENGINE FORCES & MOMENTS ~~AC~~

BEFORE GOING FURTHUR, IT IS IMPORTANT TO DISCUSS THE PROPULSIVE FORCES & MOMENTS GENERATED & APPLIED DURING AIRCRAFT FLIGHT. IN ORDER TO PROPERLY USE THE EQUATIONS OF MOTION FOR FLIGHT, THESE FORCES & MOMENTS MUST BE DETERMINED.

AN EXAMPLE HERE WILL HAVE PROPULSIVE FORCES DEFINED IN THE ~~STABIL~~ WIND AXIS SYSTEM.

D_{RAM} → RAM DRAG. THE DRAG ASSOCIATED WITH THE TURNING MOMENTUM OF THE AIR TUBE INTO THE ENGINE

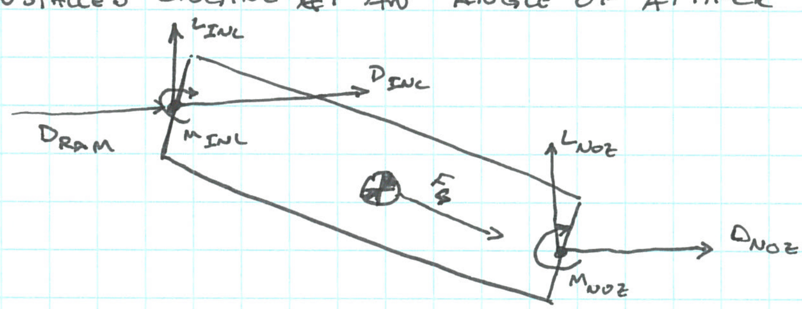
$D_{INL/NOZ}$ → INLET DRAG & NOZZLE ~~DRAG~~ DRAG. DRAG BOOK KEPT BY THE PROPULSION SIDE ACCOUNTING FOR DRAG @ THE INLET/NOZZLE

$L_{INL/NOZ}$ → INLET LIFT & NOZZLE LIFT. LIFT .. ....

$M_{INL/NOZ}$ → INLET & NOZZLE PITCHING MOMENT. PM....

F_G → GROSS THRUST. THE PROPULSIVE FORCE GENERATED BY AN ENGINE. THIS ACTS THROUGH A DESIGNATED REFERENCE POINT: THE THRUST CENTER.

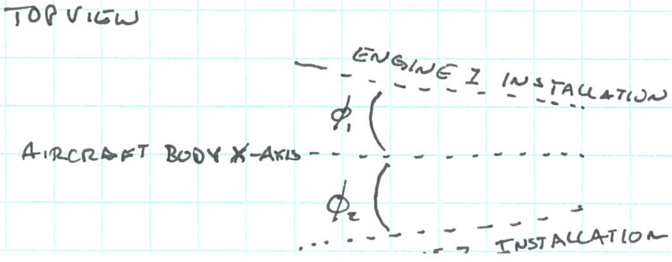
INSTALLED ENGINE AT AN ANGLE OF ATTACK



SIDE VIEW

TYPICALLY THE ENGINES ARE INSTALLED W/ NO INCIDENCE ANGLE, FOR WHEN THIS IS NOT THE CASE, THE ~~THRUST~~ GROSS THRUST MUST BE ASSUMED TO ACT ALONG A DIFFERENT AXIS THAN THE BODY AXIS. THIS IS ACCOUNTED FOR WITH AN INSTALLATION ANGLE CORRECTION

TOP VIEW



ϕ_1 & ϕ_2 ARE INSTALLATION ANGLES.

04/07/19

IN ORDER TO USE THESE TERMS IN THE DEFINED EOM, THEY MUST FIRST BE TRANSFERRED TO THE BODY AXIS COORDINATE SYSTEM.

$$F_{X_{RAM}} = -D_{RAM} \cos\alpha \cos\beta$$

$$F_{Y_{RAM}} = -D_{RAM} \cos\alpha \sin\beta$$

$$F_{Z_{RAM}} = -D_{RAM} \sin\alpha \cos\beta$$

RAM DRAG BODY AXIS FORCES

$$F_{X_{INL}} = -D_{INL} \cos\alpha \cos\beta + L_{INL} \sin\alpha \cos\beta$$

$$F_{Y_{INL}} = 0$$ → ASSUME NO SIDE FORCE COMPONENT

$$F_{Z_{INL}} = -D_{INL} \sin\alpha \cos\beta - L_{INL} \cos\alpha \cos\beta$$

INLET COMPONENT (SAME FOR NOZZLE)

$$\rightarrow F_{X_{ENG}} = F_G \cos\phi + F_{X_{RAM}} + F_{X_{INL}} + F_{X_{NOZ}}$$

$$F_{Y_{ENG}} = F_G \sin\phi + F_{Y_{RAM}}$$

$$F_{Z_{ENG}} = F_{Z_{RAM}} + F_{Z_{INL}} + F_{Z_{NOZ}}$$

ENGINE MOMENTS MUST GO THROUGH A SIMILAR TRANSFORMATION TO GET THE MOMENTS ACTING THROUGH THE CENTER OF GRAVITY.

DEPENDING ON RAM DRAG APPLICATION POINT & THRUST CENTER APPLICATION POINT IN RELATION TO THE CENTER OF GRAVITY, THE RAMDRAG & GROSS THRUST WILL GENERATE ROLL, PITCH, & YAWING MOMENTS THAT MUST BE ACCURATELY CAPTURED.

04/09/19

WIND TUNNEL TESTING (WTT)

WIND TUNNELS ARE FACILITIES THAT ALLOW FOR SCALE AIRCRAFT MODELS OR SHAPES TO BE PLACED IN A CONTROLLED FLOW FIELD. THE PARTICULAR BENEFITS OF WIND TUNNEL TESTING ARE TO ALLOW ENGINEERING CONTROL OVER ALL ASPECTS OF THE TEST. THIS INCLUDES MODEL SHAPE/CONFIGURATION, MODEL ATTITUDE/INCLINATIONS RELATIVE TO FLOW, AND FLOW PROPERTIES INCLUDING SPEED, REYNOLD'S NUMBER, AND OTHER STATE VARIABLES.

DIFFERENT FACILITIES OFFER DIFFERENT TYPES OF DATA ~~COLLECTION~~ REGION COLLECTIONS. WHILE DISCUSSING DIFFERENT TYPES OF TESTING, FACILITIES WILL BE OUTLINED FOR THEIR CAPABILITIES.

WTT MODEL-MOUNTING & DATA COLLECTION

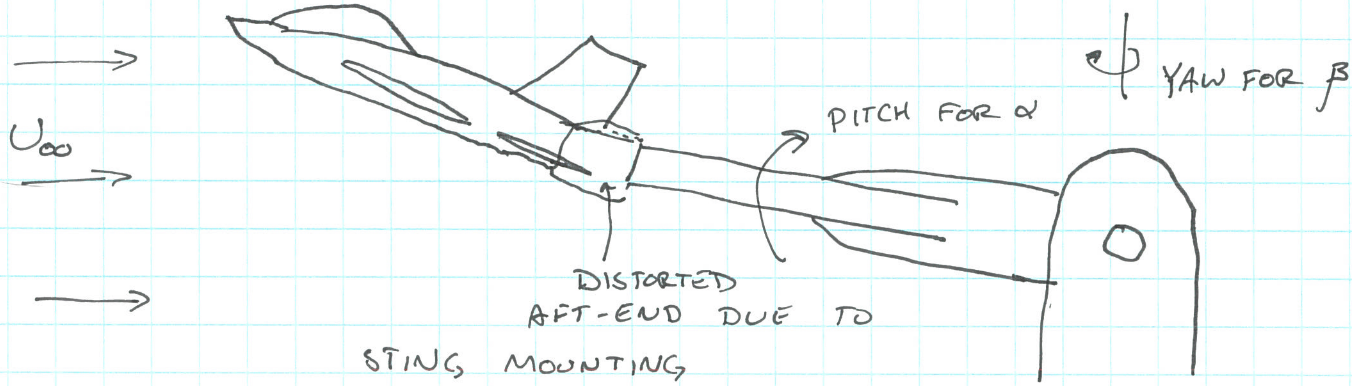
DEPENDING ON THE TYPE OF TEST BEING CONDUCTED, DIFFERENT TYPES OF MODEL MOUNTING TECHNIQUES ARE USED.

STATIC TESTING → THIS IS THE MOST COMMON TYPE OF TESTING ~~WHICH~~ AND IS THE ~~ME~~ TYPICAL TESTING DONE WHEN THINKING OF WIND TUNNELS.

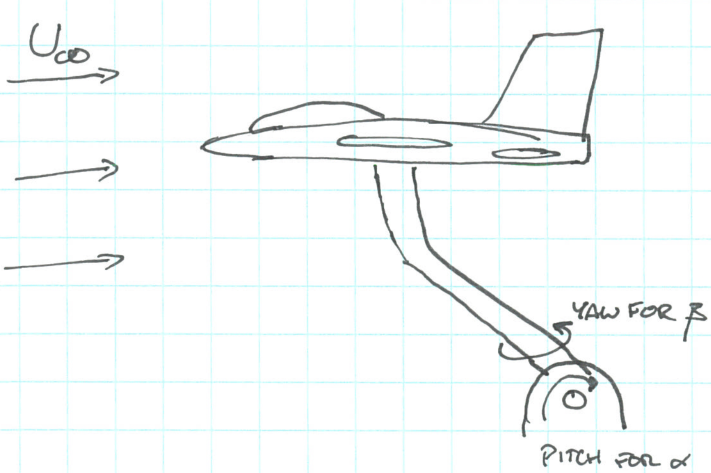
HERE, A ~~STING~~ BALANCE IS MOUNTED TO A STING THAT ~~ARE~~ THEN HAS THE AIRCRAFT MODEL BUILT ONTO THE BALANCE SO THAT IT MAY BE PLACED INTO THE TUNNEL TO MEASURE AERODYNAMIC CHARACTERISTICS. THERE ARE SEVERAL ~~TYPES~~/WAYS STINGS CAN BE MOUNTED TO THE AIRCRAFT ~~MOD~~ BALANCE. AFT-MOUNTED STINGS MOUNT TO/~~THROAT~~ THROUGH THE AFT END OF THE MODEL.

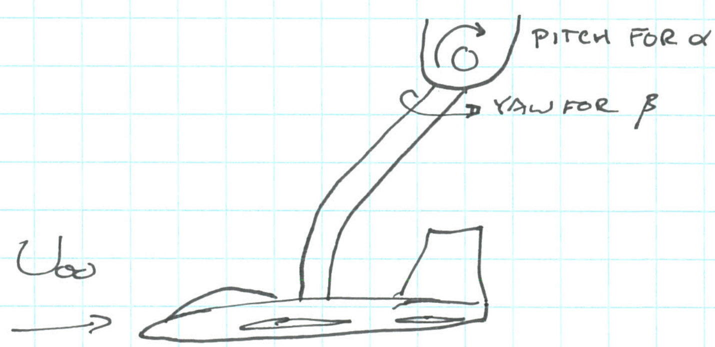
04/09/19

AFT-MOUNTED STINGS DON'T DISRUPT THE MAIN AERODYNAMIC SURFACES (WING, FLAPS, AILERONS, RUDDERS, HORIZONTAL TAILS), BUT THEY TYPICALLY CAUSE AFT-END DISTORTION TO EXIST. THIS HAPPENS BECAUSE THE STING LOADS REQUIRE THE STING TO BE LARGER THAN AFT-END PERTURBERANCES (ENGINE HOLLOWED OUT).



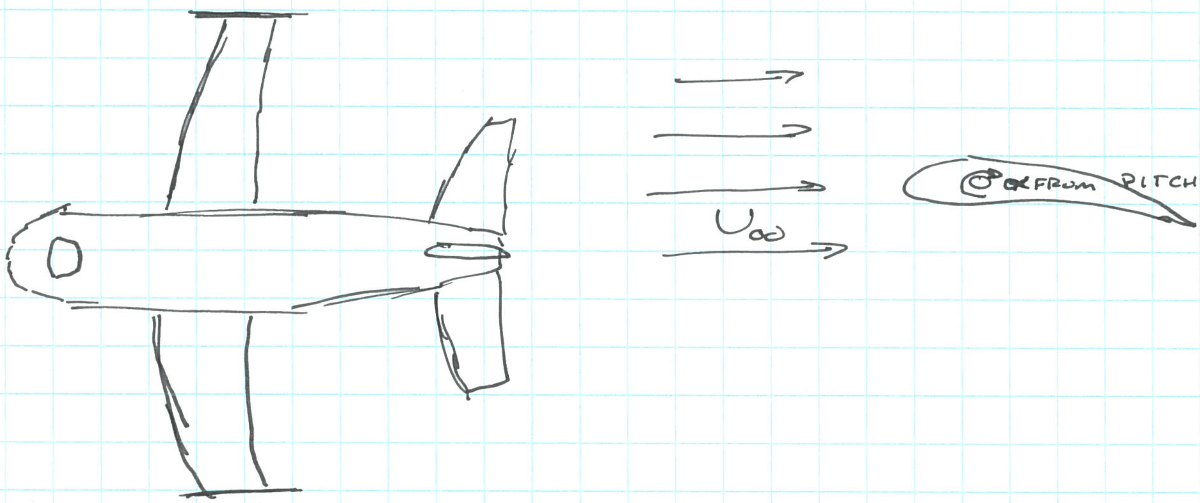
TOP &/OR BOTTOM MOUNTED STINGS MOUNT AS SUCH TO THE AIRCRAFT. THESE TOO ~~INTRODUCE~~ CAN INTRODUCE DISTURBANCES IN THE FLOW THAT ARE NOT TRUE-AIRCRAFT REPRESENTATIVE. HOWEVER, SOME TESTING MAY CALL FOR THESE TYPES OF MOUNTS WHEN THERE IS LITTLE ROOM TO MOUNT ELSEWHERE.





04/09/14

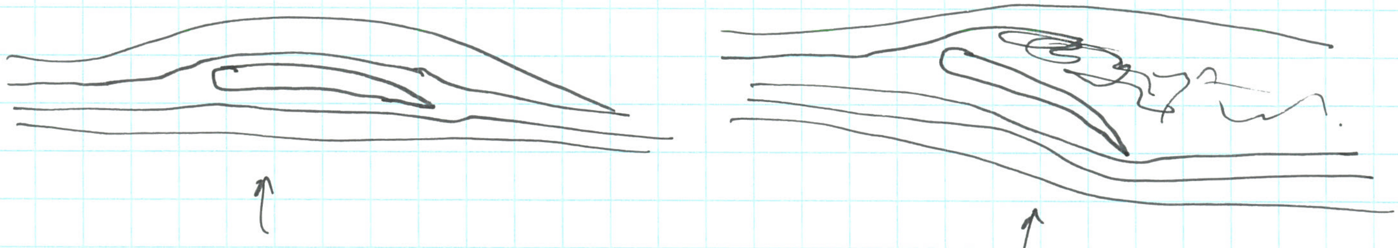
WING-TIP MOUNTED TESTING HAS THE WING TIPS FIXED TO A MOVABLE JOINT TO ALLOW FOR PITCH. THIS TYPE OF APPROACH CAN ALSO BE USED TO STUDY AIRFOILS IN WIND TUNNEL SECTIONS. TYPICALLY, THE TESTING OF AIRFOILS USES SMALL CROSS-SECTION TUNNELS & FLOW VISUALIZATION METHODS TO VIEW THE FLOW OVER AN AIRFOIL.



MOUNTED AT WINGTIPS

FLOW VISUALIZATION

FLOW VISUALIZATION CAN BE DONE IN WIND TUNNELS THROUGH SEVERAL DIFFERENT TECHNIQUES. ONE METHOD IS TO INSERT SMOKE-STREAMS INTO THE TUNNEL TO SEE THE STREAMLINES OF AIR & HOW THEY FLOW OVER ~~THE~~ & INTERACT WITH THE MODELS.

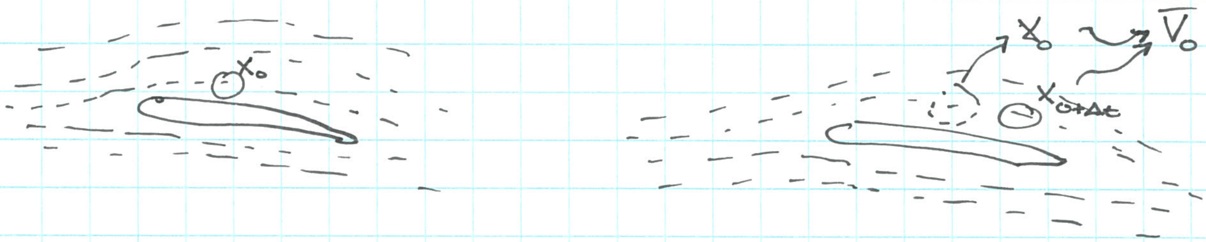


NON-SEPARATED FLOW

FLOW SEPARATION ON UPPER SURFACE

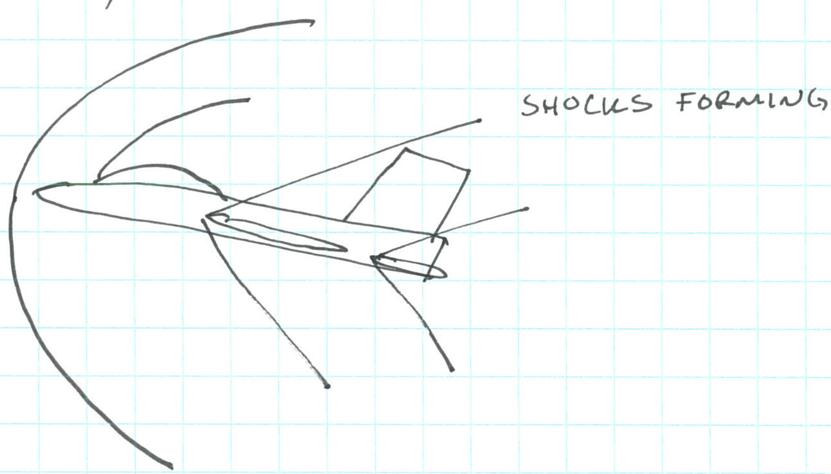
04/08/19

ANOTHER METHOD INCLUDES PARTICLE-TRACKING TO NOT ONLY DETERMINE HOW THE FLOW INTERACTS WITH THE MODEL, BUT ALSO TRACK THE VELOCITY OF THE FLOW WITHIN THE GIVEN FLOW FIELD. THROUGH THE USE OF PARTICLES, STROBE-LIGHTS & TRACKING SOFTWARE, THE PARTICLES CAN BE TRACED THROUGH THE WIND TUNNEL & AROUND THE MODELS.



$t = t_o$ $\qquad$ $t = \Delta t + t_o$

SCHLIEREN PHOTOGRAPHS ARE USED TO DETERMINE DENSITY GRADIENTS WITHING THE FLOW & CAN SHOW LOCALIZED DIFFERENCES IN FLOW FIELDS THROUGH DIFFERENT OPTICAL PATH LENGTHS. THESE CAN EASILY SHOW THE FORMATION & LOCATIONS OF SHOCKS DEVELOPING ON AN AIRFOIL/MODEL.



A FINAL TECHNIQUE IS THROUGH THE USE OF PRESSURE-SENSITIVE PAINT THAT CAN BE COATED ONTO THE AIRCRAFT MODEL. THIS PAINT WILL CHANGE COLOR DEPENDING ON THE PRESSURE APPLIED AND CAN GIVE INSIGHT INTO FLOW CHARACTERISTICS.

04/09/19

ROTARY BALANCE TESTING

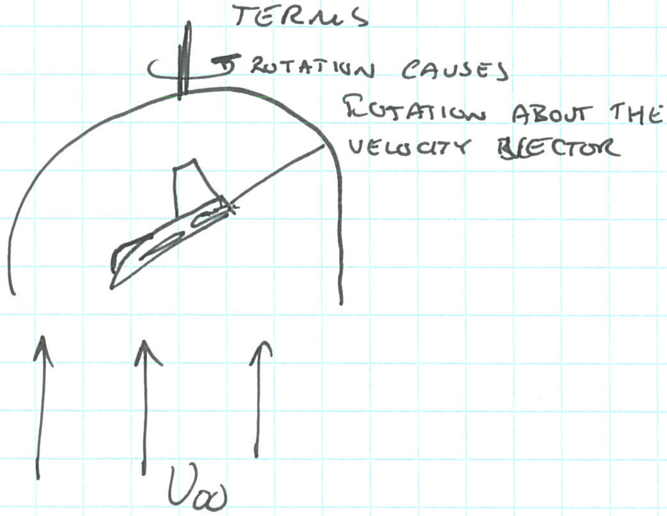
ROTARY BALANCE & FORCED-OSCILLATION TESTING CAN BE CONDUCTED TO EXTRACT AERODYNAMIC DYNAMIC DERIVATIVES.

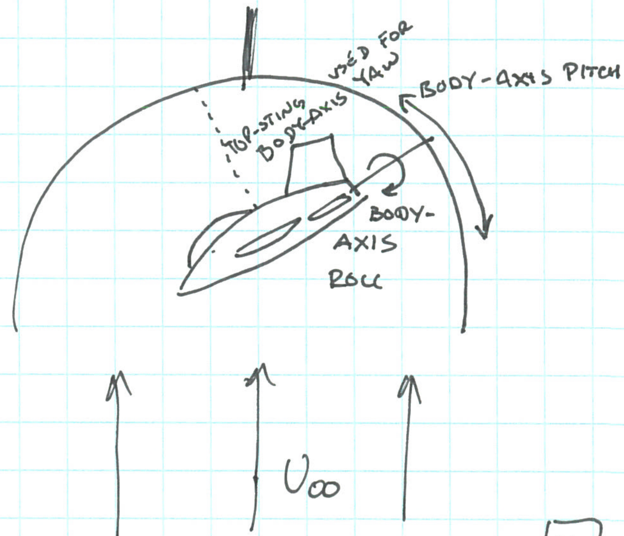
THIS TESTING INVOLVES ROTATING THE AIRCRAFT MODEL IN THE FLOW OF THE WIND TUNNEL.

ROTARY TERMS/TESTING IS WHEN THE AIRCRAFT MODEL IS ROTATED ABOUT THE VELOCITY VECTOR FOR A GIVEN α/β COMBINATION. THIS TESTING IS DONE TO COLLECT THE STEADY-STATE ROTATION TERMS $\left(\Omega b/2V_T\right)$

FORCED-OSCILLATION TESTING IS WHEN AN ATTITUDE (α/β) IS SET & INDIVIDUAL BODY-AXIS ROTATION RATES ARE INTRODUCED TO THE AIRCRAFT MODEL. THIS TESTING ALLOWS FOR THE DYNAMIC DERIVATIVES &/OR OSCILLATOR RATE TERMS TO BE EXTRACTED

COMBINED MOTION TESTING IS WHEN TWO OR MORE ROTARY OR FORCED OSCILLATION TESTING OCCURS AT THE SAME TIME. THIS IS TYPICALLY TESTED FOR CHECK-CASES TO ENSURE SUPER POSITION SUMMATION IS WORKING FOR THE ROTARY BALANCE/FORCED OSCILLATION TERMS





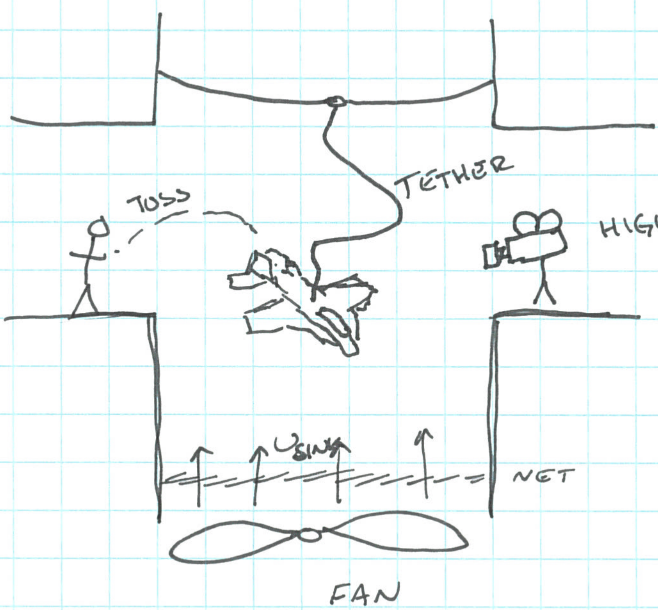
04/09/19

FREE SPIN TESTING

ALSO KNOWN AS "FRISBEE TESTING."

A DYNAMICALLY SCALED ~~CONTROLLAB~~ MODEL IS CREATED WITH REMOTE CONTROLLED SURFACES. IT IS THEN TOSSED INTO A VERTICAL TEST SECTION WITH PRO-SPIN CONTROLS. ONCE A SPIN DEVELOPS (IF IT DOES), ANTI-SPIN CONTROLS ARE INPUT.

THIS TESTING ASSESSES AN AIRCRAFTS' SPIN MODES & CAN BE USED IN CONJUNCTION WITH ROTARY BALANCE TESTING TO CONFIRM AERODYNAMIC COEFFICIENTS THROUGH SPIN ANALYSIS.



USING A HIGH SPEED CAMERA, THE X, Y, Z POSITIONS IN THE TUNNEL AND EULER ANGLES CAN BE DETERMINED.

04/09/19

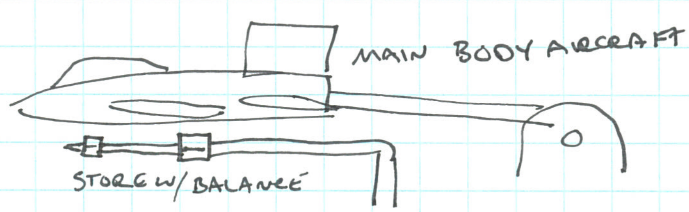
~~STORE SEPARATION TESTING~~

MULTI - BALANCE TESTING

WIND TUNNEL TESTING IS NOT LIMITED TO A SINGLE BALANCE SEVERAL TYPES OF TESTS USE MULTIPLE BALANCES TO DETERMINE AERODYNAMIC FORCES & MOMENTS FOR TWO - BODY SCENARIOS.

STORE LOADS TESTING → A STORE IS MOUNTED TO THE MAIN BODY OR WING OF AN AIRCRAFT AND IT CONTAINS IT'S OWN BALANCE WITHIN. THIS ALLOWS FOR THE COLLECTION OF AERODYNAMIC LOADS ON THE STORE WHILE IT IS IN THE PRESENCE OF THE AIRCRAFT. THIS DATA CAN BE USED BY LOADS & STRUCTURES TEAMS TO DETERMINE INTERNAL AIRCRAFT LOADS/STRESSES.

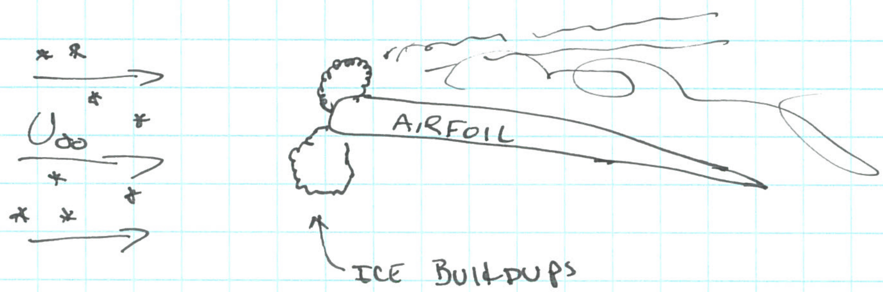
STORE SEPARATION TESTING → AN AIRCRAFT MODEL IS PLACED IN THE TUNNEL LIKE OTHER TESTS, BUT ANOTHER STING-MOUNTED BALANCE IS INCLUDED WITH A STORE MODELED. THIS SECOND STING CAN BE MOVED IN RELATION TO THE AIRCRAFT MODEL TO COLLECT THE STORE AERODYNAMIC DATA FOR POST- SEPARATION FROM THE AIRCRAFT. SOME ADVANCED TUNNELS CAN INCLUDE COLLECTED AERODYNAMIC DATA AS FEEDBACKS TO DRIVE STORE MOVEMENT TO SEE IF CONTACT BETWEEN STORE & AIRCRAFT WILL BE MADE POST-SEPARATION.



04/09/19

ICING WIND TUNNELS

SOME WIND TUNNELS ARE BUILT THAT ALLOW FOR FREEZING WATER TO BE INJECTED INTO THE FLOW STREAM BEFORE THE AIR REACHES THE AIRCRAFT MODEL. THIS SLURRY FULLY FREEZES WHEN CONTACT IS MADE WITH THE MODEL. THIS TYPE OF TESTING CAN BE DONE TO STUDY THE FORMATION OF ICE ON WINGS & CONTROL SURFACES



ICE BUILDUP ON LEADING EDGES OF WINGS CAN CAUSE SEPARATION TO OCCUR AT LOWER ANGLES OF ATTACK. UNDERSTANDING THIS FORMATION CAN HELP WITH PREVENTATIVE DESIGN MEASURES TO BE USED EARLY IN THE DESIGN OF AN AIRCRAFT.

MODEL SCALES

MODEL SCALES CAN VARRY & TYPICALLY DEPEND ON THE TEST SECTION OF THE CHOSEN WIND TUNNEL FACILITY & THE ALLOWABLE LOADS ON THE FACILITY'S STING MOUNTS. BOTH STATIC & DYNAMIC LOADS NEED TO BE CONSIDERED WHEN SCALING A MODEL.

NOTE THAT SOME FACILITIES (NASA AMES 80'x120') CAN ALLOW FOR FULL-SIZED AIRCRAFT. THIS TUNNEL OPERATES AT LOW SPEEDS ONLY AS POWER REQUIREMENTS WOULD BECOME TO LARGE.

04/10/19

IN SOME CASES, NOT ALL OF THE FULL-SCALE DETAILS ~~ARE~~ CAN BE MODELED WHEN BUILDING A TO-SCALE MODEL. DETAILS SUCH AS PROPER FLAP MECHANISMS, AIR DATA INSTRUMENTATION, AND LIGHTS/ANTENNAE CAN BE TOO SMALL ON A SCALED MODEL TO CREATE. IT IS IMPORTANT TO UNDERSTAND THIS & KNOW THE DIFFERENCES BETWEEN THE SCALED & FULL SIZED MODELS.

TYPES OF WIND TUNNEL TESTS

EACH WIND TUNNEL TEST NEEDS TO BE APPROACHED WITH THE IDEA OF QUANTITATING DATA TO BE COLLECTED. ALREDY MENTIONED ARE THE FLOW VIS, ICING & STORE SEPARATION TESTING, BUT THERE ARE SEVERAL MORE.

STABILITY & CONTROL

HERE A MULTITUDE OF AXIS SWEEPS WITH DIFFERENT CONTROL SURFACE DEFLECTIONS ARE PERFORMED THIS DATA GOES TOWARDS THE S&C DATABASE & IS TYPICALLY USED BY FLYING QUALITIES TEAMS FOR THE SAKE OF BUILDING CONTROL LAW DESIGNS.

A TYPICAL TEST WILL INCLUDE α SWEEPS, β SWEEPS, SEVERAL MACH NUMBERS (IF TUNNEL ALLOWS), CONTROL SURFACE DEFLECTIONS (SINGLE, MULTIPLE & DURING α & β SWEEPS), & CAN INCLUDE DIFFERENT CONFIGURATIONS IF STORES ARE CARRIED ON THE MODEL

A SUBSET OF S&C TESTING IS HIGH ANGLE OF ATTACK TESTING WHERE DATA IS COLLECTED ~~AT~~ UP TO & PAST THE STALL AOA. THESE ARE TYPICALLY LOW SPEED DUE TO LOAD LIMITS ON THE STING.

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PERFORMANCE TESTING

THIS TESTING FOCUSES ON EXTRACTING DRAG POLARS OUT OF WIND TUNNEL DATA THAT IS COLLECTED. CARE IS TAKEN TO ENSURE ALL AIRCRAFT PERTURBURANCES ARE MODELLED AS ACCURATELY AS POSSIBLE. ON TOP OF THIS, DATA TOLERANCES ARE TYPICALLY TIGHTENED TO ~~[illegible]~~ REDUCE UNCERTAINTY ON THE COLLECTED DATA.

A SUBSET OF THIS TESTING INCLUDE'S HIGH LIFT TESTING. THIS IS WHEN THE HIGH LIFT DEVICES & ~~[illegible]~~ LANDING GEAR ARE EXTENDED TO SIMULATE THE LANDING CHARACTERISTICS OF THE AIRCRAFT.

WIND TUNNEL DATA CORRECTIONS

THERE ARE TOO MANY CORRECTIONS TO BE ABLE TO COVER THEM ALL, HERE WILL BE DISCUSSED SOME OF THE MOST COMMON CORRECTIONS APPLIED.

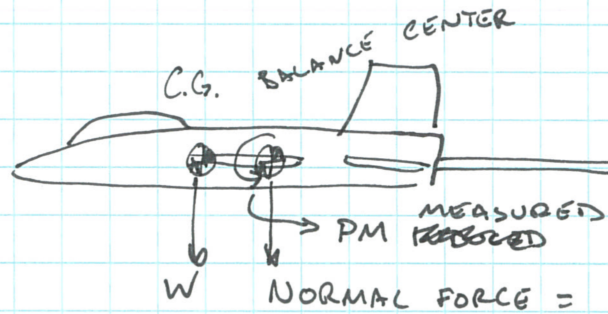
WEIGHT TARES

WIND OFF MEASUREMENTS ARE TAKEN ~~A~~ TO DETERMINE THE MODEL WEIGHT MEASUREMENTS ON THE BALANCE. THESE MUST BE SUBTRACTED OFF OF THE BALANCE READINGS ~~WHERE~~ AS ONLY AERODYNAMIC FORCES & MOMENTS ARE SOUGHT DURING TESTING.

THESE ~~[illegible]~~ MEASUREMENTS ARE TAKE OVER THE RANGE OF MOTION THAT TESTING WILL BE OCCURING AT.

04/10/19

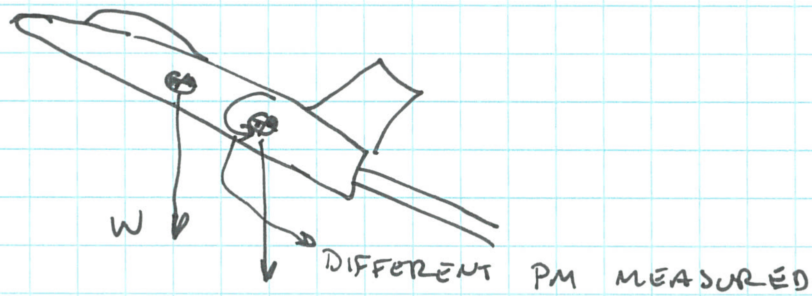
$\alpha = 0$



NORMAL FORCE = WEIGHT

AXIAL FORCE = $\emptyset$

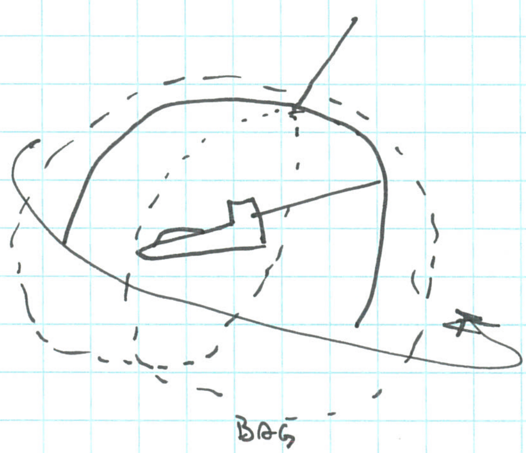
α = POSITIVE



$NF = W \sin\alpha$

$AF = W \cos\alpha$

ROTARY BALANCE TESTING REQUIRES THAT NOT ONLY THESE STATIC MEASUREMENTS BE TAKEN, BUT THAT THE MODEL ALSO BE SPUN TO DETERMINE THE MODEL INERTIAL ~~FREE~~ TARES THAT MUST BE SUBTRACTED TOO. THIS IS DONE IN A "TARE BALL" OR "TARE BAG" THAT ENCOMPASSES THE MODEL & ROTATES WITH THE MODEL DURING WIND-OFF TARES. THE OBJECTIVE IS TO ISOLATE THE BALANCE LOADS DUE TO ROTATION. THE BAG CAUSES THE AIR MASS TO ROTATE ~~AROUND~~ WITH THE MODEL SO THAT NO AIR LOADS ARE ACTIVE ON THE BALANCE



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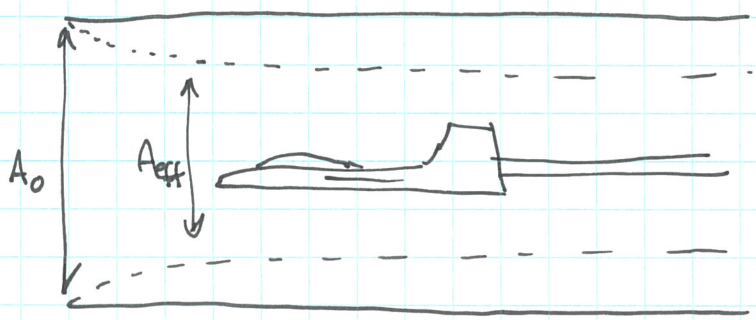
AFT END DISTORTION

AS MENTIONED BEFORE, ~~SO~~ THE MODEL CAN SOMETIMES BE DISTORTED WHE MOUNTED TO A STING. CORRECTIONS CAN BE MADE FROM OTHER STING MOUNTED TESTS, OR MOST RECENTLY, THROUGH CFD. THIS CORRECTIONS ARE APPLIED TO SIMULATE A "TRUE AFT END".

TUNNEL WALL EFFECTS

BLOCKAGE → ~~MODE~~ THE MODEL & TUNNEL WALLS ~~HAV~~ HAVE BOUNDARY LAYER GROWTH THAT EFFECTIVELY REDUCES THE CROSS-SECTIONAL AREA OF THE STREAM TUBE OF AIR THAT IS FLOWING OVER THE MODEL.

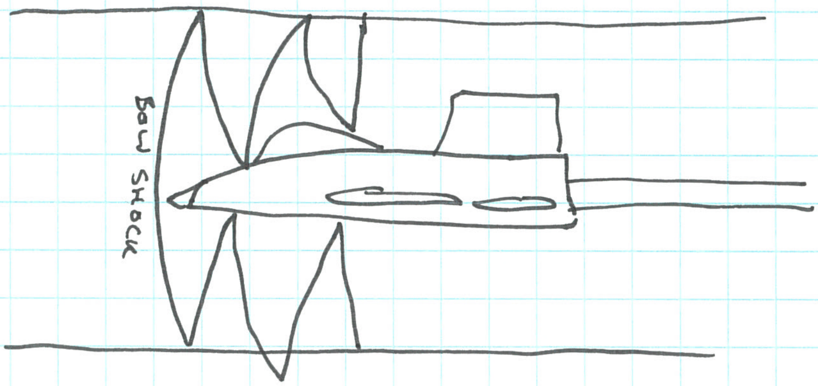


SOME TUNNELS HAVE POROUS WALLS THAT CAN SUCK THE BOUNDARY LAYER OUT.

MODEL-WALL INTERACTIONS → DURING HIGH ANGLE OF ATTACK TESTING THE MODEL CAN COME CLOSE TO THE TUNNEL WALLS INTRODUCING AN INTERFERENCE EFFECT BETWEEN THE TWO.

04/10/19

SHOCK REFLECTION – DURING SUPERSONIC TESTING, ~~THE~~ SHOCKS CAN FORM AROUND THE MODEL. THESE SHOCKS CAN BE REFLECTED OFF OF THE WALLS AND IMPINGE BACK ON THE MODEL. POROUS WALLS CAN HELP REDUCE THESE EFFECTS.



TRANSONIC TESTING CAN BE ESPECIALLY DIFFICULT DUE TO A FORMING BOW SHOCK THAT IS NEAR NORMAL-PLANE TO THE MODEL. THIS MAKES TRANSONIC TESTING ONE OF THE LEAST TESTED AREAS (IN MY PRACTICE). PLUS AIRCRAFT DON'T TEND TO HANG OUT NEAR MACH 1.0 FOR VERY LONG, THEY JUST TRANSITION THROUGH.

BUOYANCY CORRECTIONS → THE STATIC PRESSURE CAN CHANGE ALONG THE LENGTH OF THE TUNNEL. THESE CHANGES IN PRESSURES CAUSE FLOW DIRSTURBANCES & NEED TO BE ACCOUNTED FOR

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

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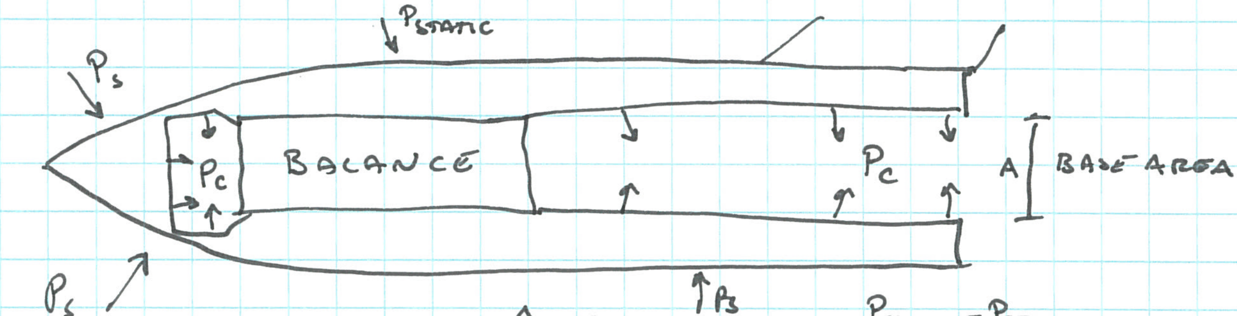
CAVITY PRESSURE CORRECTION

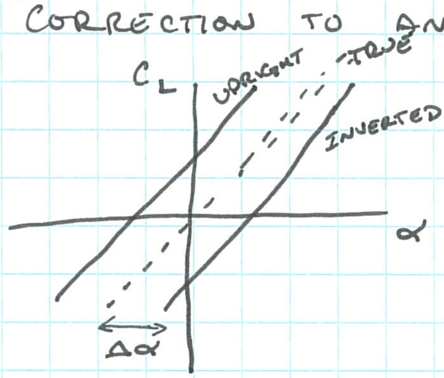
INTERNAL CAVITY PRESSURES ACT ON THE BALANCE. TYPICALLY EFFECT AXIAL FORCE MEASUREMENTS & ARE IMPORTANT FOR PERFORMANCE TESTING (NOT IMPORTANT FOR HIGH AOA TESTING).

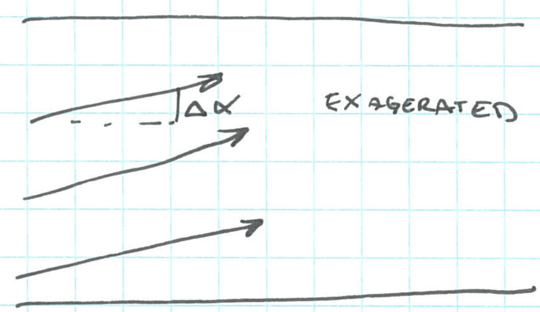


$$\text{CORRECTION} = \frac{A}{S} C_p \qquad C_p = \frac{P_{CAVITY} - P_{STATIC}}{\bar{q}}$$

FLOW ANGULARITY

CHECKS TO SEE IF THE FLOW WITHIN THE TUNNEL HAS ANY ANGULARITY TO IT (α). INVERTED & UPRIGHT RUNS ARE CONDUCTED TO DETERMINE CORRECTION TO ANGLE OF ATTACK.





$\Delta\alpha$ CALCULATED TO COLLAPSE THE INVERTED & UPRIGHT DATA SETS.

04/10/19

CALCULATING DOWNWASH FROM WT DATA

ASSUMING THAT THE TAIL IS A SYMMETRIC AIRFOIL, THE ANGLE OF ATTACK FOR ZERO LIFT & ZERO PITCHING MOMENT WILL BE $\alpha = 0°$. USING THIS KNOWLEDGE, ALONG WITH COLLECTED WIND TUNNEL DATA FOR TAIL ON & TAIL OFF, THE DOWNWASH ANGLE ON THE TAIL CAN BE CALCULATED.

SUBTRACTING TAIL O~~FF~~ DATA FROM TAIL OFF DATA CAN PROVIDE THE INCREMENTAL EFFECT OF INCLUDING THE TAIL:

$$C_{X_{SH\_ON}} = C_{X_{TAIL\,ON}} - C_{X_{TAIL\,OFF}}$$

USING THIS TO FIND THE TAIL DEFLECTION TO SATISFY NO INCREMENTAL TAIL DEFLECTION AT EACH ANGLE OF ATTACK

$$\delta_{H_0} = \delta_H \left[\text{FOR } C_{X_{SH\_ON}} = 0 \right]$$

REARRANGING THE DOWNWASH CALCULATION:

$$\alpha_{TAIL} = \alpha_{TRUE} + \delta_H - \alpha_{DW} = 0 \quad (\text{FOR } \delta_{H_0})$$

GETS

$$\rightarrow \alpha_{DW} = \alpha_{TRUE} + \delta_{H_0}$$

PLOTTING TAIL POWER VS. α_{TAIL} CAN PROVIDE INSIGHT INTO WHEN THE TAIL BEGINS TO STALL & INDICATES REGIONS OF NON-LINEAR CONTROL POWER.

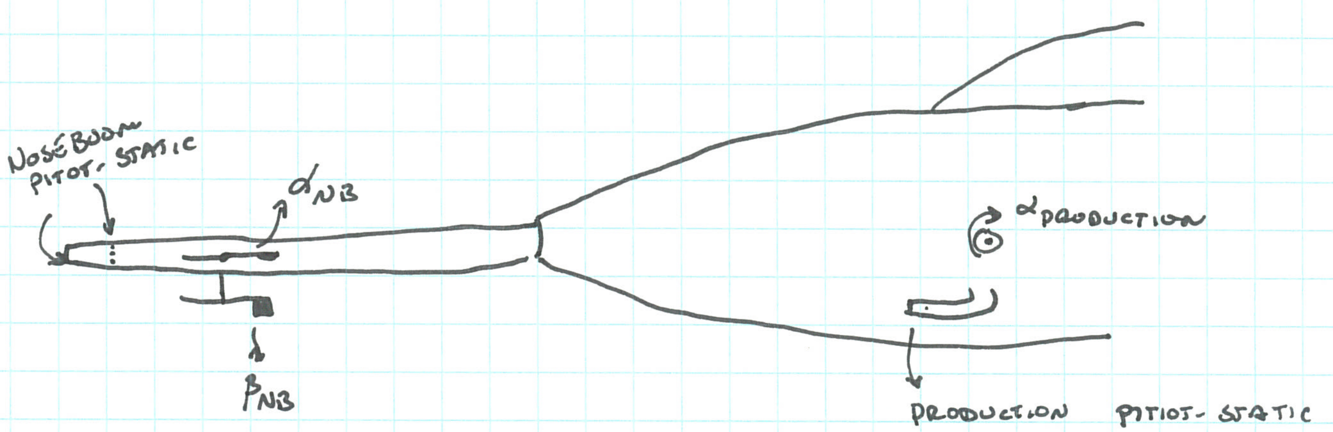
04/12/19

FLIGHT TESTING

AIRCRAFT USED FOR FLIGHT TESTING ARE TYPICALLY MODIFIED TO INCLUDE EXTRA INSTRUMENTATION TO COLLECT HIGHER FIDELITY AIR DATA & STATE VARIABLES THAN THOSE COLLECTED FROM ON-BOARD PRODUCTION INSTRUMENTS.

EVEN THOUGH THIS ADDED INSTRUMENTATION IS TYPICALLY OF HIGHER FIDELITY, IT CAN STILL REQUIRE CHECKS & CORRECTIONS.

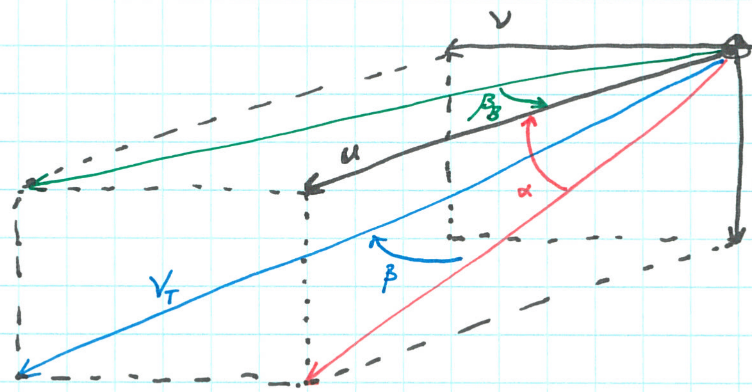
A VERY COMMON INSTRUMENT FOR FLIGHT TESTING IS A NOSE BOOM. THIS DEVICE IS ATTACHED ~~TO~~ THE FRONT OF THE AIRCRAFT & EXTENDS OUTWARD INTO THE FREE STREAM. BEING OUT IN THE FREE STREAM FURTHER PROVIDES A MORE ACCURATE READING FOR FREE STREAM PARAMETERS (α, β, V_T). DIFFERENCES BETWEEN THESE ~~MEA~~ "TRUE" MEASUREMENTS & THE PRODUCTION MEASUREMENTS CAN BE QUANTIFIED & USED TO CREATE SOURCE ERROR CORRECTIONS TO GO FROM PRODUCTION MEASUREMENTS TO "TRUE" MEASUREMENTS. PRODUCTION MEASUREMENTS ARE INFLUENCED BY THE BODY OF THE AIRCRAFT. FLOW MOVEMENT AROUND THE AIRCRAFT CAUSES ERRONEOUS MEASUREMENTS THAT SHOULD BE CORRECTED



04/12/19

SOME FLIGHT TEST CORRECTIONS

GOING BACK TO THE DEFINITIONS OF ANGLE OF ATTACK & SIDESLIP



ANGLE OF ATTACK (α) CAN BE DIRECTLY MEASURED FROM A NOSE BOOM AS IT ACTS IN THE CORRECT PLANE

β_B IS DIRECTLY MEASURED TOO & CAN BE CONVERTED USING THE WEATHER VANE CORRECTION TO GET TRUE SIDESLIP

WEATHER VANE CORRECTION TO SIDESLIP:

$$\beta = \tan^{-1}(\cos\alpha \tan\beta_B)$$

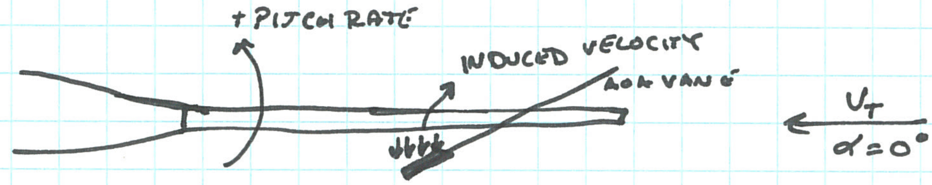
TRUE AIRSPEED CAN BE DETERMINED FROM THE PITOT - STATIC MEASUREMENTS

$$\frac{P_T}{P_S} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

$$a = \sqrt{\gamma R T}$$

$$V_T = M a$$

ANOTHER CORRECTION IS NEED FOR α & β DUE TO ROTATIONAL RATES EXPERIENCED BY THE AIRCRAFT.



~~THE~~ PITCH RATE INDUCES A VELOCITY ON THE AOA VANE WHICH HAS A LARGER SURFACE AT THE AFT END, CAUSING THE VANE TO ROTATE & MEASURE AN ERRONEOUS ANGLE.

BECAUSE THE ERROR IS INTRODUCED INTO VELOCITY TERMS, THAT IS ~~WHERE THEY~~ HOW THE CORRECTION SHOULD BE APPLIED:

$$u_M = V_{T_M} \cos\alpha_M \cos\beta_M$$
$$v_M = V_{T_M} \sin\beta_M$$
$$w_M = V_{T_M} \sin\alpha_M \cos\beta_M$$

"M" DENOTES MEASURED

$$u_C = u_M - qz + ry$$
$$v_C = v_M - rx + pz$$
$$w_C = w_M - py + qx$$

"C" DENOTES CORRECTED
X, Y, & Z ARE DISTANCES TO REFERENCE POINT TAKEN FOR CENTER OF ROTATION.

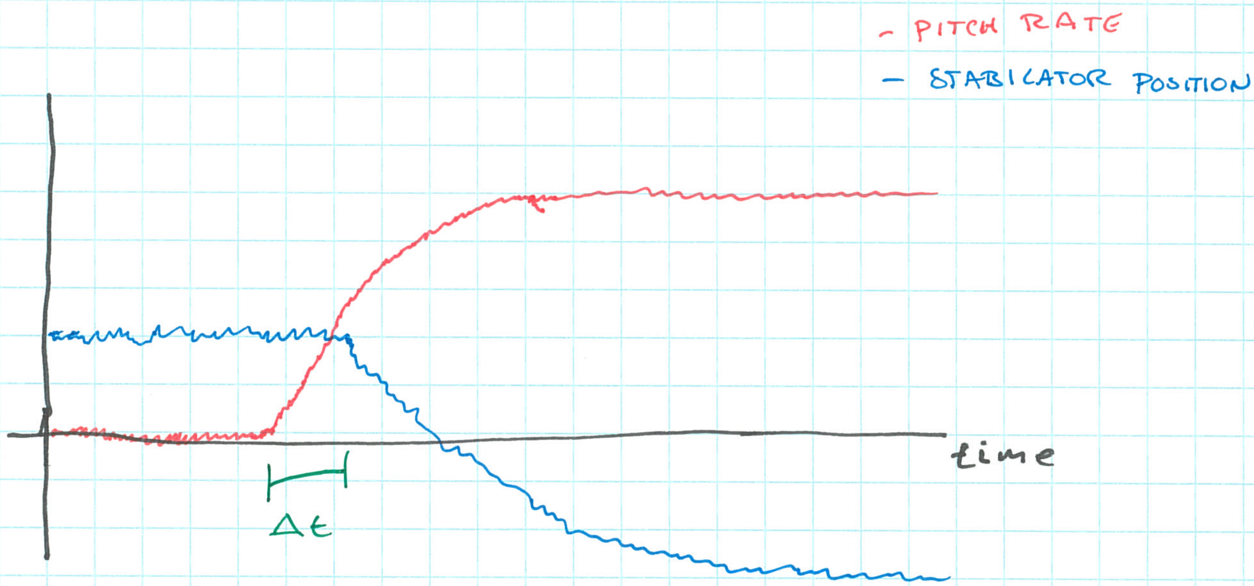
$$V_{T_C} = \sqrt{u_C^2 + v_C^2 + w_C^2}$$
$$\alpha_C = \tan^{-1}\left(\frac{w_C}{u_C}\right)$$
$$\beta_C = \sin^{-1}\left(\frac{v_C}{V_{T_C}}\right)$$

NOTE THAT DURING FLIGHT TESTING THERE WILL TYPICALLY BE MULTIPLE SOURCES FOR SIGNALS. IF A DIFFERENT DEVICE, LIKE AN INERTIAL NAVIGATION SYSTEM OR GPS ARE RECORDING u, v, & w THESE VALUES CAN ALL BE CHECKED AGAINST EACH OTHER.

04/12/19

JUST BECAUSE INFORMATION WAS RECORDED DURING TESTING DOESN'T MEAN THAT IT IS TIME SYNCED TOGETHER. RECORDED PARAMETERS MAY BE COMING FROM SEVERAL DIFFERENT DEVICES THAT ARE SENDING INFORMATION AT DIFFERENT RATES.

ONE COMMON CHECK IS TO ENSURE THAT THE RECORDED FLIGHT CONTROL SURFACES ARE TIME SYNCED WITH THE RATES & ACCELERATIONS RECORDED. IF ANY LEADS/LAGS ARE IDENTIFIED THEN THE SIGNALS SHOULD BE CORRECTED BEFORE ANY AERODYNAMIC ANALYSIS IS STARTED.



Δt → PITCH RATE BEGINS Δt s BEFORE ANY SURFACES ARE MOVED. SURFACE SIGNALS SHOULD BE ADJUSTED BY Δt SECONDS TO ENSURE TIMES LINE UP CORRECTLY