VLM Tool for IDS Integration

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Abstract

This paper is dedicated to a very specific type of analysis tool (VLM - Vortex Lattice Method) to be integrated in a IDS - Integrated Design System, tailored for the usage of small aircraft industry. The major interest is to have the possibility to simulate at very low computational costs a preliminary set of aerodynamic characteristics for basic aerodynamic global characteristics (Lift, Drag, Pitching Moment) and aerodynamic derivatives for longitudinal and lateral-directional stability analysis. This work enables fast investigations of the influence of configuration changes in a very efficient computational environment. Using experimental data and/or CFD information for a specific calibration of VLM method, reliability of the analysis may me increased so that a first type (iteration zero) aerodynamic evaluation of the preliminary 3D configuration is possible. The output of this tool is basic state aerodynamic and associated stability and control derivatives, as well as a complete set of information on specific loads on major airframe components.

The major interest in using and validating this type of methods is coming from the possibility to integrate it as a tool in an IDS system for conceptual design phase, as considered for development for CESAR project (IP, UE FP6).

Introduction

The vortex lattice method used in this approach resembles a basic quasi-steady membrane velocity boundary integral equation formulation for potential flow. The main purpose for using this tool is to enable fast analysis for global aerodynamic characteristics of a configuration, mainly for longitudinal stability analysis, with reasonable level of accuracy for lateral-directional stability derivatives and control derivatives ([1], [3], {5]).

The method is widely used in industry for aerodynamic estimates for conceptual and preliminary design predictions. The method provides good insight into the aerodynamics of wings, including interactions between lifting surfaces. Typical analysis uses (in a design environment - Figure 1) include:

- Predicting the configuration neutral point for initial configuration layout, the effects of wing placement and canard and/or tail size and location;
- Finding the lift curve slope, CL_a, approach angle of attack, etc.
- Finding the induced drag, CD_i, from the spanload in conjunction with farfield methods;
- Estimation of controls and device deflection effectiveness;
- Investigating the aerodynamics of interacting surfaces.

Other type of design applications, mainly with respect to other types of detailed analysis for a real industrial project include:

- Initial estimates of twist to obtain a desired spanload;
- Root bending moment evaluation;
- Starting point for finding a camber distribution in purely subsonic cases.

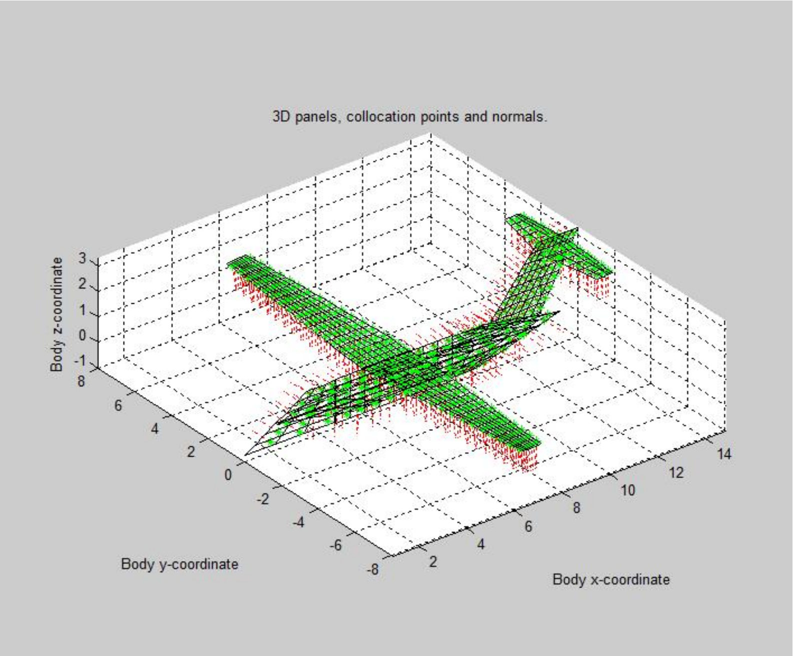


Figure 1 - Typical VLM representation for a CS-23 aircraft

VLM Aerodynamic Model

Here we present a model initially developed for the wing bound vorticity using a lattice of constant dipole panels, which are equivalent to vortex rings in a velocity formulation. The radiation condition is satisfied through the use of vortex ring elements, while the “no normal flow penetration through the mean surface” condition is satisfied through the solution of a linear system for the strengths of the vortex rings. In order to represent vorticity in the domain, the model utilizes a collection of vortex wake filaments in a wake sheet lattice (Figure 2). The wake sheet strength is prescribed by ensuring that a zero spanwise vorticity Kutta condition is satisfied at the trailing edge ([2],[4],[6]).

Due to the necessity to automate simulations, the model extends the vortex wake behind the lifting surface to at least 20 chord lengths in the direction of the freestream velocity. This long wake ensures that the steady state lift will be achieved for the current state. Several variations of wake positions have been tested; across these variations, little overall change in the aerodynamic forces was observed.

The vortex lattice method computes forces and moments directly from the vortex strengths and the prescribed free stream velocity. As such, the induced drag is neglected in the computation of forces. The lack of induced drag plays a negligible role in most simulation results, and in situations where induced drag is important, variations in simulation results become apparent.

A variation from the standard model is implemented via a Trefftz analysis for the induced drag.

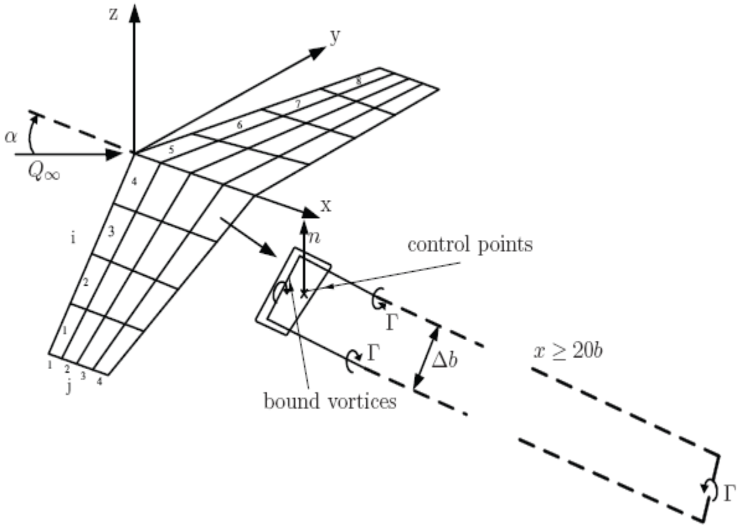


Figure 2 - The vortex lattice model for VLM method.

Notes:

1. The vortex lattice method implemented for this investigation has known drawbacks which are consistent with vortex lattice methods in general. The usage of a simple quasi-steady flat sheet wake model is one source of error. Furthermore, the use of a low order ring vortex model causes slow force and moment values convergence when the panel discretization is increased. Additional errors manifest themselves due to the lack of body thickness. Errors which are thickness dependent, such as moment center position, moment and force values, and other finer details are neglected in the vortex lattice model. Although these effects are traditionally low order effects, mild changes in stability derivatives may lead to changes in the dynamic response.

2. The VLM method should always be calibrated with experimental data to provide an indication of the agreement between numerical calculation and experiment to get final reliable results because of the neglected viscous effects.

3. Since VLM is based on solutions to Laplace's equation, it is subject to the same basic theoretical restrictions that apply to Panel Method (PM). VLM and PM methods are similar because:

- singularities are placed on a surface;
- the non-penetration condition is satisfied at a number of control points;
- the singularity strengths is determined solving a system of linear algebraic equations.

4. VLM is different from PM mainly because of the following:

- singularities are not distributed over the entire surface;
- it is oriented toward combinations of thin lifting surfaces;
- it is oriented toward lifting effects;
- boundary conditions are applied on a mean surface, not the actual surface.

Geometry Representation for VLM - CS-23 aircraft example

The basic tool is to be used for evaluation of simplified configurations, as taken from preliminary design environments in an intuitive way (Figure 3). The global concept behind the geometrical representation is based on lifting surface parameterisation.

The global geometry is considered as a sequence of lifting airframe components, where the analogy to the main lifting surface (wing) is as presented in Figure 4. Amperage and vertical tail are considered using a similar approach.

Airframe parameterisation

Input for the considered tool is the basic representation of a CS-23 aircraft configuration, as expressed in standard engineering drawings and presented in Figure 3. This type of representation is often coming from the IDS environment, using dedicated tools for pre-design based on a conceptual approach.

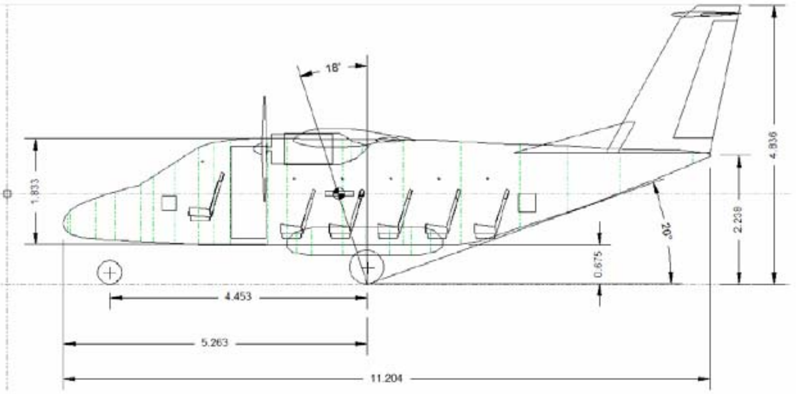


Figure 3 – Global aircraft representation in IDS - AeroTAXI configuration

Wing parameterization is based on the 4 sections presented in Figure 3. There are 4 sections, where one can split in 2, as follows:

- Sections with no controls (1 and 4). This is generally the case for root and wing tips areas.
- Sections with controls (flap and aileron regions).

A combination of the 4 section, using linear variation of basic geometrical data, enables the consideration of most of classical wing design.

All other lifting surfaces (e.g. amperage) and vertical tail may be considered using this parameterisation. Also, specific controls on such surfaces are considered as follows:

- rudder is equivalent to the aileron as TE control
- elevator is equivalent to flaps as TE control
- LE controls may not be present in a specific design.

Fuselage parameterisation is considered via the cruciform concept, where 2 lifting surfaces are considered for the projections in xy and xz planes. Each of the surfaces is further divided into 3 sections, for nose, central fuselage and tail.

Any other important airframe (e.g. engines nacelles) may be considered using the analogy with the fuselage.

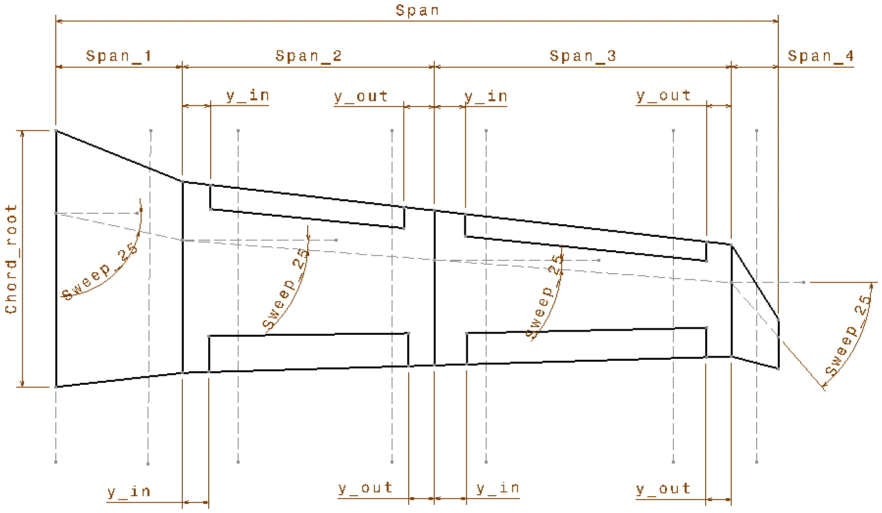
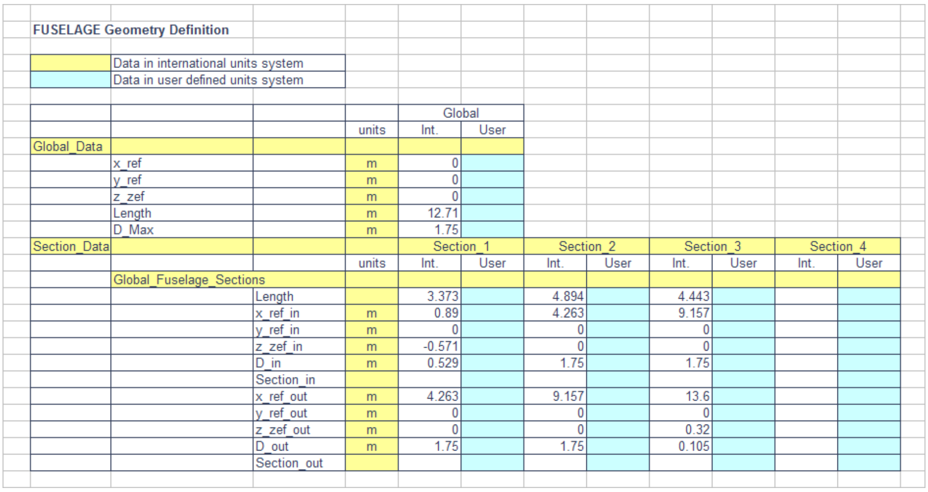


Figure 4 – Wing geometry parametrisation

The most convenient way to use the initial parameterised geometry as presented is based on specific templates. We consider a different template for any surface in the geometry, both for lifting surfaces (wing, tail, etc.) and for fuselage (2 in cruciform arrangements) and equivalents (booms, nacelles, etc.) as follows.

Templates for geometry inputs in IDS

A template for IDS inputs (as considered in CESAR Project) is presented in Figure 5 for fuselage and in Figure 6 for the empennages (including wing), with some data for a basic aircraft configuration in the sub-commuter category (unpressurised, high wing, twin engine).



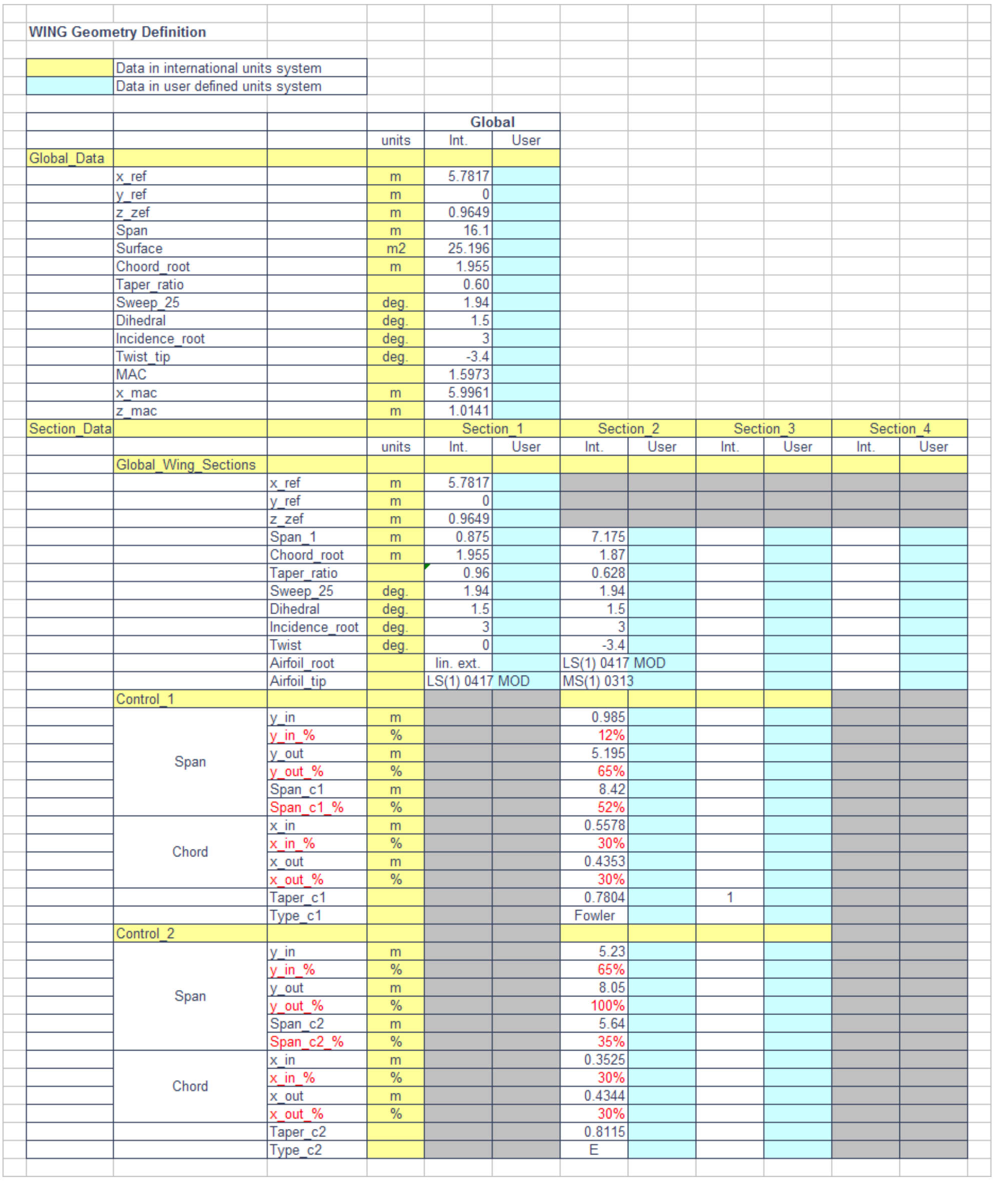
FUSELAGE Geometry Definition

🟨	Data in international units system
🟦	Data in user defined units system

				Global							
			units	Int.	User						
Global_Data											
	x_ref		m	0							
	y_ref		m	0							
	z_zef		m	0							
	Length		m	12.71							
	D_Max		m	1.75							
Section_Data				Section_1		Section_2		Section_3		Section_4	
			units	Int.	User	Int.	User	Int.	User	Int.	User
	Global_Fuselage_Sections										
		Length		3.373		4.894		4.443			
		x_ref_in	m	0.89		4.263		9.157			
		y_ref_in	m	0		0		0			
		z_zef_in	m	-0.571		0		0			
		D_in	m	0.529		1.75		1.75			
		Section_in									
		x_ref_out	m	4.263		9.157		13.6			
		y_ref_out	m	0		0		0			
		z_zef_out	m	0		0		0.32			
		D_out	m	1.75		1.75		0.105			
		Section_out									

Figure 5 – Fuselage geometry template - Test configuration

The usage of a parameterised geometry and templates for specific airframes is a key element in the overall IDS process, where optimization tools make full usage of such parameters.



WING Geometry Definition

🟨 Data in international units system
🟦 Data in user defined units system

				Global							
			units	Int.	User						
Global_Data											
	x_ref		m	5.7817							
	y_ref		m	0							
	z_zef		m	0.9649							
	Span		m	16.1							
	Surface		m2	25.196							
	Choord_root		m	1.955							
	Taper_ratio			0.60							
	Sweep_25		deg.	1.94							
	Dihedral		deg.	1.5							
	Incidence_root		deg.	3							
	Twist_tip		deg.	-3.4							
	MAC			1.5973							
	x_mac		m	5.9961							
	z_mac		m	1.0141							
Section_Data				Section_1		Section_2		Section_3		Section_4	
			units	Int.	User	Int.	User	Int.	User	Int.	User
	Global_Wing_Sections										
		x_ref	m	5.7817							
		y_ref	m	0							
		z_zef	m	0.9649							
		Span_1	m	0.875		7.175					
		Choord_root	m	1.955		1.87					
		Taper_ratio		0.96		0.628					
		Sweep_25	deg.	1.94		1.94					
		Dihedral	deg.	1.5		1.5					
		Incidence_root	deg.	3		3					
		Twist	deg.	0		-3.4					
		Airfoil_root		lin. ext.		LS(1) 0417 MOD					
		Airfoil_tip		LS(1) 0417 MOD		MS(1) 0313					
	Control_1										
	Span	y_in	m			0.985					
		y_in_%	%			12%					
		y_out	m			5.195					
		y_out_%	%			65%					
		Span_c1	m			8.42					
		Span_c1_%	%			52%					
	Chord	x_in	m			0.5578					
		x_in_%	%			30%					
		x_out	m			0.4353					
		x_out_%	%			30%					
		Taper_c1				0.7804		1			
		Type_c1				Fowler					
	Control_2										
	Span	y_in	m			5.23					
		y_in_%	%			65%					
		y_out	m			8.05					
		y_out_%	%			100%					
		Span_c2	m			5.64					
		Span_c2_%	%			35%					
	Chord	x_in	m			0.3525					
		x_in_%	%			30%					
		x_out	m			0.4344					
		x_out_%	%			30%					
		Taper_c2				0.8115					
		Type_c2				E					

Figure 6 – Wing geometry template - Test configuration

Also, for data sharing and information exchange between IDS and more sophisticated CAD environments (e.g. CATIA), specific tools are used to reconstruct parts of the geometry using specific scripts. The templates are common for all such collaborative tools.

Note: In this approach the high lift and control surfaces are considered as in Figure 6, for every specific area (if present). The implementation is based on the lifting surface theory and quasi-steady flat sheet wake model. This type of implementation has some well known problems/corrections if compared to “real” derivatives coming from experiments.

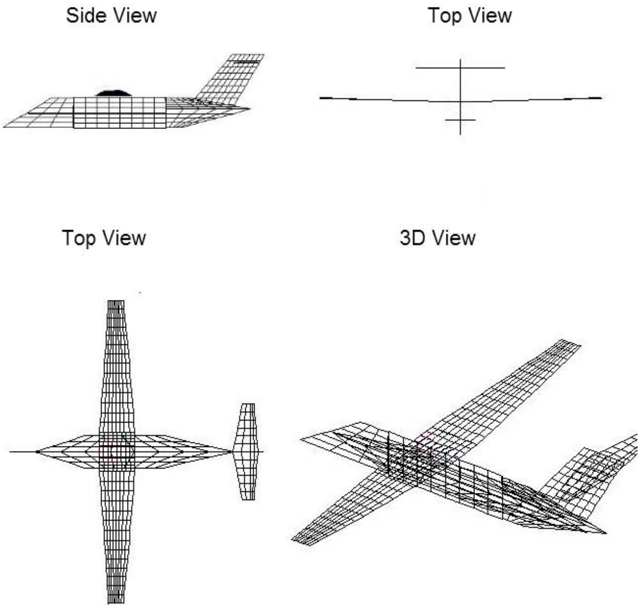


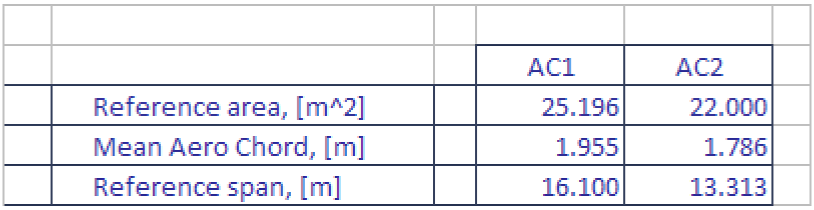
Figure 7 – 3D VLM geometry - Test configuration

The final full 3D configuration for VLM analysis for a CS-23 aircraft configuration is presented in Figure 7. This configuration is to be analyzed in order to evaluate tool performance with respect to other similar tools and also with respect to experimental data.

VLM Tool evaluation for CESAR Project

a. Basic aerodynamic state evaluation

All computations have been performed for the following basic geometrical data for AC1 (low speed turboprop) and AC2 (high speed business jet) reference configurations, as defined in CESAR Project:



	AC1	AC2
Reference area, [m^2]	25.196	22.000
Mean Aero Chord, [m]	1.955	1.786
Reference span, [m]	16.100	13.313

Table 1 – Basic reference data for AC1/AC2

Basic aerodynamic computed state using VLM tool, state relevant for AC1 and AC2 is presented in Figure 8.

b. Derivatives evaluation

Longitudinal aerodynamic derivatives are defined in the standard body fixed coordinates system. Longitudinal and Lateral-directional aerodynamic derivatives of the given aerodynamic configuration are calculated and presented ([7], [8]) for several incidences.

Control derivatives are calculated and presented in Table 3 for several incidences for specific controls.

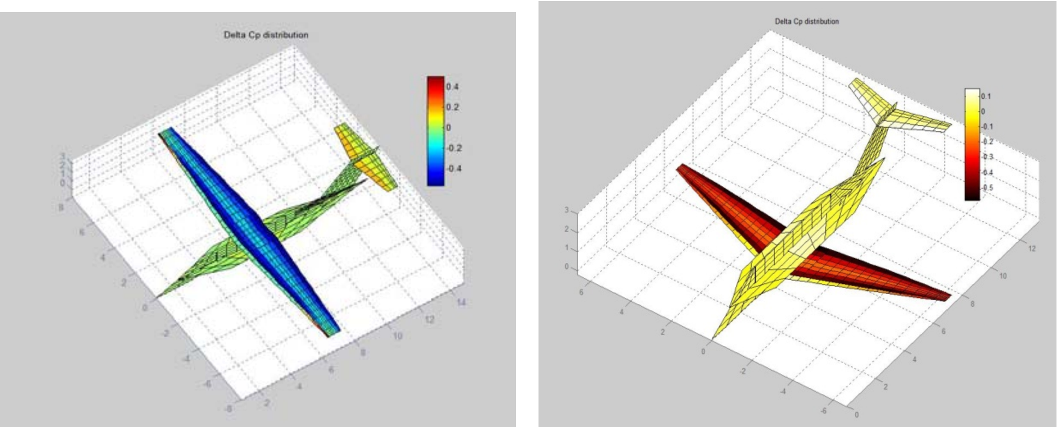


Figure 8 – VLM analysis for AC1 and AC2 reference configurations

VLM tool evaluation and assessment

Comparison between Cessna aircraft company's 172 data [9] and VLM code at INCAS is provided in this chapter. A synthetic view is presented in Table 2.

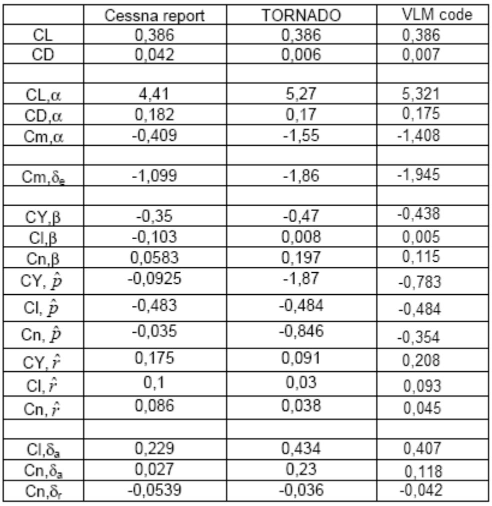
To further validate the VLM computational model, comparisons have been made for data and coefficients measured by the Cessna aircraft company [Cessna, 1957]. At the same time, several data from TORNADO code [10] are presented for comparisons.

The aircraft model used is the Cessna 172. The aircraft mass considered for reference was 1000 kg. The evaluation was done at cruise configuration, i.e. 54.54 m/s, alpha 4.9 degrees at 1.500 meters altitude.

Comments:

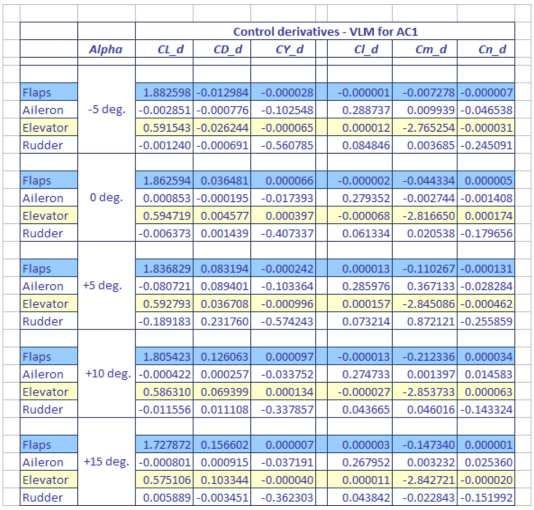
- VLM computation was set to yield this result in order to ensure that the comparison was made same flight condition as in reference.
- The VLM value is lower, which is expected since no friction drag is modeled. The angle of attack is low, which means low induced drag.
- The lift-curve slope for the real aircraft is lower than the computed value because of fuselage and thickness effects.

- The Cessna report value is for the trimmed condition. Influence also comes from the different reference points.
- Elevator power derivative. The potential flow solution from VLM is higher, possibly to reference point differences and boundary layer effects.
- Side force due to sideslip. The fuselage has a large impact here.
- Rolling moment due to sideslip, differences come from offset in reference point z-coordinate.
- Yawing moment due to sideslip, or directional stability derivative. The potential flow solution is much stiffer than the Cessna value. Probable causes are fuselage and thickness effects.
- Side force due to roll rate. The position of the rotation axis plays a big role here.
- Side force due to yaw rate. The LEX of the fin and the fuselage is not modeled in VLM, which explains the higher Cessna value.
- Rolling moment due to yaw rate. The LEX of the fin and the fuselage is not modeled in VLM, which explains the higher Cessna value.
- Yaw damping moment (due to yaw rate). The LEX of the fin and the fuselage is not modeled in VLM, which explains the higher Cessna value.
- Aileron power derivative, the potential flow solution of VLM shows a higher value.
- Yaw moment due to aileron deflection, the Cessna value is much lower due to the stabilizing moments of the fuselage.
- Rudder power derivative, geometric differences fuselage effects the comparison.



	Cessna report	TORNADO	VLM code
CL	0,386	0,386	0,386
CD	0,042	0,006	0,007
CL,α	4,41	5,27	5,321
CD,α	0,182	0,17	0,175
Cm,α	-0,409	-1,55	-1,408
Cm,δ_e	-1,099	-1,86	-1,945
CY,β	-0,35	-0,47	-0,438
Cl,β	-0,103	0,008	0,005
Cn,β	0,0583	0,197	0,115
CY, $\hat{p}$	-0,0925	-1,87	-0,783
Cl, $\hat{p}$	-0,483	-0,484	-0,484
Cn, $\hat{p}$	-0,035	-0,846	-0,354
CY, $\hat{r}$	0,175	0,091	0,208
Cl, $\hat{r}$	0,1	0,03	0,093
Cn, $\hat{r}$	0,086	0,038	0,045
Cl,δ_a	0,229	0,434	0,407
Cn,δ_a	0,027	0,23	0,118
Cn,δ_r	-0,0539	-0,036	-0,042

Table 2 – Comparisons with Cessna data

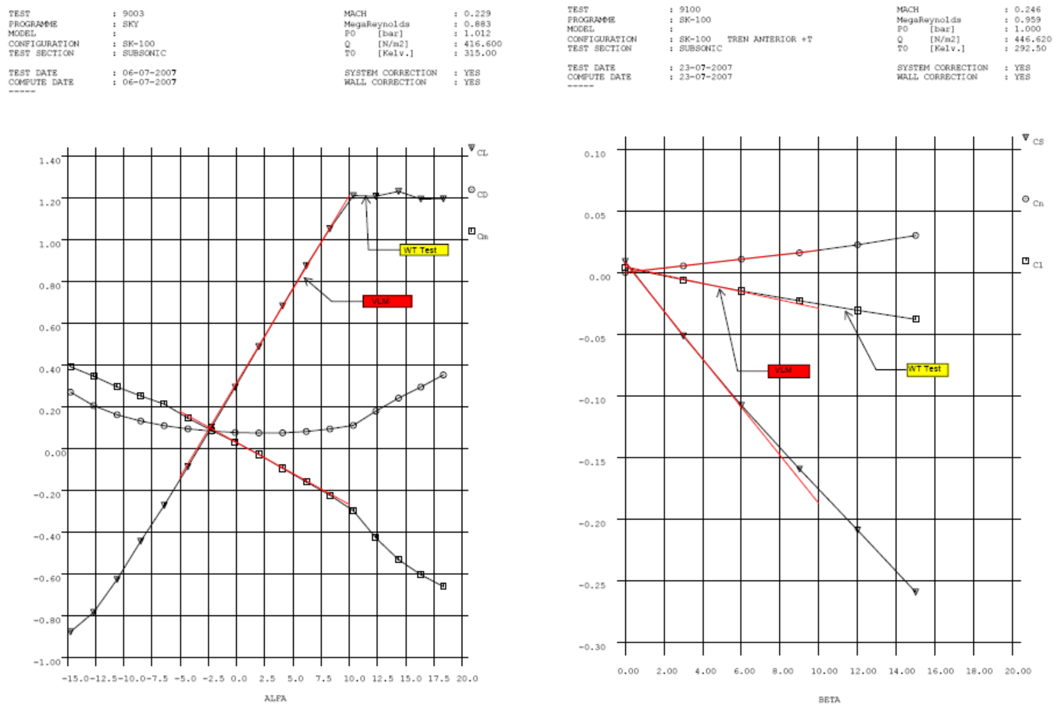


		Control derivatives - VLM for AC1					
	Alpha	CL_d	CD_d	CY_d	Cl_d	Cm_d	Cn_d
Flaps	-5 deg.	1.882598	-0.012984	-0.000028	-0.000001	-0.007278	-0.000007
Aileron		-0.002851	-0.000776	-0.102548	0.288737	0.009939	-0.046538
Elevator		0.591543	-0.026244	-0.000065	0.000012	-2.765254	-0.000031
Rudder		-0.001240	-0.000691	-0.560785	0.084846	0.003685	-0.245091
Flaps	0 deg.	1.862594	0.036481	0.000066	-0.000002	-0.044334	0.000005
Aileron		0.000853	-0.000195	-0.017393	0.279352	-0.002744	-0.001408
Elevator		0.594719	0.004577	0.000397	-0.000068	-2.816650	0.000174
Rudder		-0.006373	0.001439	-0.407337	0.061334	0.020538	-0.179656
Flaps	+5 deg.	1.836829	0.083194	-0.000242	0.000013	-0.110267	-0.000131
Aileron		-0.080721	0.089401	-0.103364	0.285976	0.367133	-0.028284
Elevator		0.592793	0.036708	-0.000996	0.000157	-2.845086	-0.000462
Rudder		-0.189183	0.231760	-0.574243	0.073214	0.872121	-0.255859
Flaps	+10 deg.	1.805423	0.126063	0.000097	-0.000013	-0.212336	0.000034
Aileron		-0.000422	0.000257	-0.033752	0.274733	0.001397	0.014583
Elevator		0.586310	0.069399	0.000134	-0.000027	-2.853733	0.000063
Rudder		-0.011556	0.011108	-0.337857	0.043665	0.046016	-0.143324
Flaps	+15 deg.	1.727872	0.156602	0.000007	0.000003	-0.147340	0.000001
Aileron		-0.000801	0.000915	-0.037191	0.267952	0.003232	0.025360
Elevator		0.575106	0.103344	-0.000040	0.000011	-2.842721	-0.000020
Rudder		0.005889	-0.003451	-0.362303	0.043842	-0.022843	-0.151992

Table 3 – Tool output - AC1 control derivatives

Comparison with WT data

VLM was compared with data from SKY project at INCAS (a CS-23 class aircraft, subsonic) where WT data are available. This is because one might expect that VLM has to provide accurate results for a relatively simple configuration in a low subsonic regime.



```
TEST                : 9003                          MACH                 : 0.229
PROGRAMME           : SKY                           MegaReynolds         : 0.883
MODEL               :                               P0     [bar]         : 1.012
CONFIGURATION       : SK-100                        Q      [N/m2]        : 416.600
TEST SECTION        : SUBSONIC                      T0     [Kelv.]       : 315.00

TEST DATE           : 06-07-2007                    SYSTEM CORRECTION    : YES
COMPUTE DATE        : 06-07-2007                    WALL CORRECTION      : YES
-----
```

```
TEST                : 9100                          MACH                 : 0.246
PROGRAMME           : SK-100                        MegaReynolds         : 0.959
MODEL               :                               P0     [bar]         : 1.000
CONFIGURATION       : SK-100   TREN ANTERIOR +T     Q      [N/m2]        : 446.620
TEST SECTION        : SUBSONIC                      T0     [Kelv.]       : 292.50

TEST DATE           : 23-07-2007                    SYSTEM CORRECTION    : YES
COMPUTE DATE        : 23-07-2007                    WALL CORRECTION      : YES
-----
```

Figure 9 - VLM comparison with wt data in SKY project

VLM and CFD is different. One can expect to have precise information on the imposed flow configurations and the deflexions of controls. Therefore it is to be expected that a set of WT data and the corresponding CFD calculations have to be harmonized so that one can benefit from both analysis.

Here we present in Figure 9 are some examples of the DRMR analysis as compared with VLM analysis for a CS-23 aircraft configuration similar to AC1 in the CESAR project. In Figure 9 we have compared values for a wt experiment with the VLM computations at different incidence and Reynolds numbers.

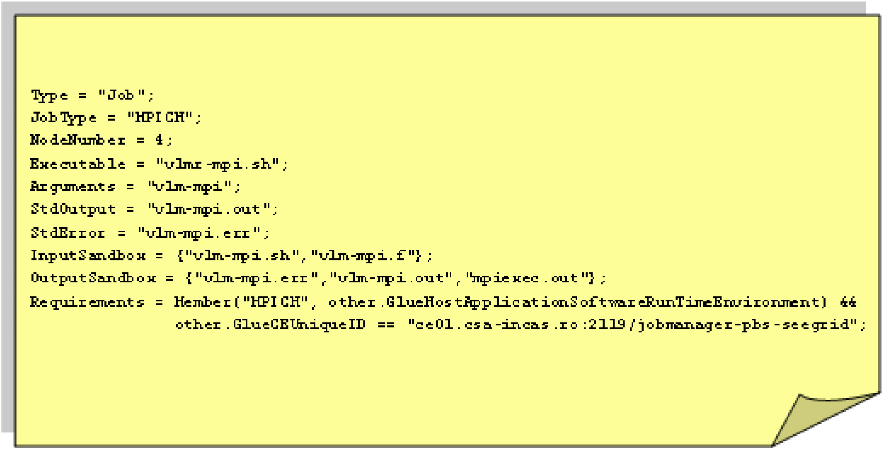
Note: For the SKY project/configuration, from a dedicated external analysis, the geometry for the model (the cruciform shape) was selected so that the angle of attack for zero lift is maching the wt data.

VLM tool integration to IDS

VLM tool is intended for integration with IDS developed at INCAS. With respect to the integration requirements, the following aspects are important.

- VLM tool is reconfigured as a “batch” type of application, able to be launched in a script initiated by the user.
- All user inputs requested for any type of analysis is reconfigured in a “.job” file, used at the beginning of any process.

- All data introduced in the database has to be visible to a process that is initiated by a user with "standard" access rights. This corresponds to a low level for data access security in a first order type of delocated access. If security is a problem, then dedicated tools for data retrieval under security are to be provided for the generation of a local database to be subject for analysis with VLM.
- Graphical representation is not a must. However, using basic graphical representation tools (e.g. GNUPlot in Linux) one can better monitor the output of the analysis, thus enhancing the quality.



```
Type = "Job";
JobType = "MPICH";
NodeNumber = 4;
Executable = "vlmr-mpi.sh";
Arguments = "vlm-mpi";
StdOutput = "vlm-mpi.out";
StdError = "vlm-mpi.err";
InputSandbox = {"vlm-mpi.sh","vlm-mpi.f"};
OutputSandbox = {"vlm-mpi.err","vlm-mpi.out","mpiexec.out"};
Requirements = Member("MPICH", other.GlueHostApplicationSoftwareRunTimeEnvironment) &&
               other.GlueCEUniqueID == "ce01.csa-incas.ro:2119/jobmanager-pbs-seegrid";
```

Figure 10 - .jdl file for VLM

Note: In CESAR project, mainly for WP5.1 activities using tools from WP1.1, the template for geometry (as presented in this paper) is given BEFORE having a complex CAD model for the configuration. Using dedicated scripts (see other deliverabled in WP 1.1) the CAD geometry is generated (in CATIA v5 format), where basic elements from the template are used as parameters for optimization.

Some Conclusions

The design of a small aircraft (CS-23 category) can only be successful if one succeeds to find an integrated optimum solution for the key disciplines aerodynamics, flight mechanics and structures. VLM is a tool that enables fast and reliable information into a compact representation that can be used in standard analytical models in stability and control.

While individual problems in the area of aerodynamics and flight mechanics can be solved using existing methods and tools, the inverse design problems can only be solved with the help of such tools as VLM. This is strongly related to the basic question:

"if some dynamic characteristic of the aircraft is bad, what airframe component is to be changed in order to preserve global dynamic characteristics" ?

The answer in this case is the usage of VLM tool in an inverse design process, where some other tools dedicated to other disciplines (e.g. structural analysis) may also be included.

VLM is to be integrated in the IDS developed at INCAS and demonstrated in CESAR Project. At the same time, this tool will be used for preliminary inputs in flight dynamics analysis. Therefore it is expected that a global evaluation of the tool will be available after several iterations with the involved tasks and activities.

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REFERENCES

[1] *D. P. Raymer*, ***Aircraft Design: A Conceptual Approach***, 3rd Ed., AIAA, Washington, 1999

[2] *Hess, J. L.*, ***"Panel Methods in Computational Fluid Dynamics",*** Annual Review of Fluid Mechanics, Vol. 22, 1990

[3] *Katz, J., and Plotkin, A.*, ***Low-Speed Aerodynamics From Wing Theory to Panel Methods***, McGraw-Hill, Inc., New York, 1991.

[4] *Lamar, J.E., and Gloss, B.B.*, "***Subsonic Aerodynamic Characteristics of Interacting Lifting Surfaces With Separated Flow Around Sharp Edges Predicted by a Vortex-Lattice Method",*** NASA TN D-7921,1975

[5] *Kalman, T.P., Rodden, W.P., and Giesing, J.*, ***"Application of the Doublet-Lattice Method to Nonplanar Configurations in Subsonic Flow",*** Journal of Aircraft, Vol. 8, No. 6, June 1971

[6] DeJarnette, F.R., ***"Arrangement of Vortex Lattices on Subsonic Wings",*** in Vortex Lattice Utilization Workshop, NASA SP-405, May, 1976.

[7] *Thomas, R.W.*, ***"Analysis of Aircraft Stability and Control Design Methods",*** AFWAL-TR-84-3038, Vol. II, App. B., "Evaluation of Aerodynamic Panel Methods," by John Koegler, May, 1984

[8] *Etkin, B. and Reid, L. D.*, ***Dynamics of Flight: Stability and Control***, John Wiley and Sons, 3rd ed., 2000.

[9] *L.L. Leisher* et al, ***Stability derivatives of Cessna aircraft***, Cessna Aircraft Company, 1957.

[10] **http://www.ave.kth.se/divisions/aero/software/tornado/tornado.html**