IMPLEMENTATION OF QUAD-M METHODOLOGY FOR HELICOPTER SYSTEM IDENTIFICATION –AN EXAMPLE WITH H-55 FLIGHT TEST

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Abstract. *This work presents results obtained from a case study for H-55 Helicopter System Identification, which was carried out by an implementation of Quad-M Methodology purposed for Jategoankar..A comparison between Stability and Control Derivatives (SCD) tables from these results and those from literature is performed, for some important flight conditions. This comparison allows us to conclude about the reliability of the method, to present preliminary SCD tables for the studied aircraft and point to possible future works.*

Keywords*: helicopter, Stability and Control Derivatives (SCD), flight test, Quad-M.*

1. INTRODUCTION

Simulations are important activities which can reduce work time and save money at different knowledge areas. Helicopter dynamic is not different. There, these activities are growing up quickly and a many industries are inverting appreciable human, material and financial resources. The recent technical literature in this field points mainly towards the development of new methods for estimating Stability and Control Derivatives (SCD), that are the basis of helicopter certification, development and design.

Some authors in Helicopter Dynamics Theory propose methodologies to perform system identification by determining SCDs using experimental data obtained from flight tests. Cookie (2002) presents and discusses Helicopter Test and Evaluation techniques and shows that there are fundamental for a successful aeronautical system identification. Tishler (2006) addresses System Identification and focuses in frequency domain methodology, presenting detailed techniques for this approach and exploiting their advantages. Padfield (2007) presents conceps regarding flying qualities and simulation modeling comparing Helicopter Flight Dynamics theory and application. Finally, Jategoankar (2006) presents a flight vehicle system identification method, based on a time domain approach, compares their advantages and problems face to frequency domain, and purposes some algorithms techniques for easy implementation using low cost computational resources.

Based on Quad-M methodology presented by Jategoankar (2006), Cruz et al. (2009a) and Cruz et al. (2009b) present a Dynamic Model for flight Simulator. These works focuses on the lateral-directional helicopter system identification problem using Output-Error Method (OEM) and Genetic and Levenberg-Marquardt Optimization Algorithms. Hereinafter, Cruz et al. approach will be called Quad-M/CTA Methodology, since it intends to improve the Jategoankar Quad-M methodology with an specific approach developed at Centro Tecnico Aeroespacial (CTA), São José dos Campos-Brazil.

Departing from Quad-M/CTA results, (Oliveira and Menegaldo, 2010a) discusses about thresholds for Gauss-Newton Optimization for Output-Error Method, applied in system identification over helicopter flight test data and concludes about the conditions needed for OEM applicability. After (Oliveira and Menegaldo, 2010b) concludes about important parameters to guarantee reliability at Quad-M/CTA process.

Results for system identification can be compared to literature results. In helicopter field of knowledge only few data is available regarding SCD. The main sources are Hefley (1979) and Padfield (2007), which are used in this work as comparison reference parameters. This work was developed under research Project approved by Post-Graduated Program in Defense Engineering at "*Instituto Militar de Engenharia (IME)"*.and the mainly sponsor is Brazilian Army Aviation (BAAv), which is a huge helicopter operator, owning different models normally utilitarian which allow special configurations in order to perform great operative and ordinary mission range. BAAv has interest to implement and develop Flight Simulators.

2. METHODOLOGY

2.1 Stability and Control Derivatives (SCD)

Helicopter Dynamic studies are based on equilibrium equation for Momentum (L, M, N) and Forces (X, Y, Z) acting on helicopter during its flight. These equations are presented as a function of linear velocities (u, v and w) and angular rates (p, q and r), referred to the typical main rotorcraft axis (x, y and z). To calculate the path flight usually Euler angles (ϕ, θ, and ψ) are used. Figure 1 shows the helicopter main axis.
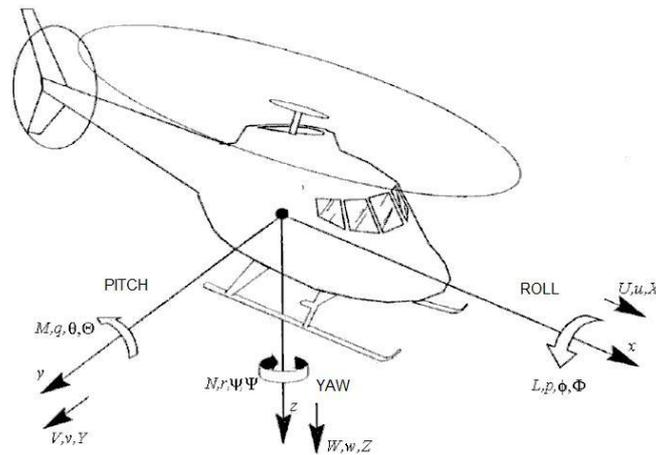
Fig. 1: Helicopter Main Axis

Dynamic equation are usually non-linear, nevertheless a linearization approach is useful to facilitate calculus. Using small disturbances in helicopter behavior from an equilibrium flight condition, it is possible to define the Stability and Control Derivatives (SCD) vector

$$
\begin{aligned}
\Theta = [& X_u, X_v, X_w, X_p, X_q, X_r, X_{d\delta c}, X_{d\delta m}, \\
& X_{d\delta l}, X_{d\delta n}, Y_u, Y_v, Y_w, Y_p, Y_q, Y_r, Y_{d\delta c}, Y_{d\delta m}, Y_{d\delta l}, \\
& Y_{d\delta n}, Z_u, Z_v, Z_w, Z_p, Z_q, Z_r, Z_{d\delta c}, Z_{d\delta m}, Z_{d\delta l}, Z_{d\delta n}, \\
& L_u, L_v, L_w, L_p, L_q, L_r, L_{d\delta c}, L_{d\delta m}, L_{d\delta l}, L_{d\delta n}, M_u, \\
& M_v, M_w, M_p, M_q, M_r, M_{d\delta c}, M_{d\delta m}, M_{d\delta l}, M_{d\delta n}, \\
& N_u, N_v, N_w, N_p, N_q, N_r, N_{d\delta c}, N_{d\delta m}, N_{d\delta l}, N_{d\delta n}]
\end{aligned}
\qquad (1)
$$

where each SCD represents a infinitesimal variation between a Force (X, Y, Z) or Moment (L, M, N) over a speed (u, v, w) or angular velocity (p, q, r), or yet a command displacement (ddc, ddb, dda, ddn). The ddc is collective command displacement; ddb or ddm is a cyclic longitudinal command displacement; dda or ddl is a cyclic lateral command displacement and ddn is a pedal command displacement.

The SCDs are represented respectively by the derivative expressions:

$$ X_u = \partial X / \partial u \quad (2); $$
$$ X_v = \partial X / \partial v \quad (3); $$

and so on.

2.2 Experimental tests

This work try to determine H-55 helicopter SCD, expressed in vector Θ. This vector represents all SCD of helicopter dynamic formulation. For each flight condition (altitude, speed, weight, CG-position) different vectors Θ of SCDs can be defined.

To carry out system identification in time dominium the 'Helimat' software was developed in Matlab R2007[®]. The computational mean employed was a Intel[®] Corel2™ CPU 6600 @ 2.4 GHz PC with 1.97 GB RAM. Helimat implements recursively the Output Error Method optimization method applying the Gauss-Newton algorithm. The criteria for accuracy validity of the SCD-Groups found are Cramer-Rao (CR) and Relative Correlation Coefficient (RCC). The initial guess used for the Helimat System Identification was found from Quad-M/CTA (Cruz et al, 2009a) results. Flight data was obtained from 16 flight test hours in a representative AS 355-F2 helicopter (also called h-H-55) with a measurement system that includes 35 flights parameters.

3. RESULTS

System identification carried out by Helimat program gave the following results, which were assembled in in nine case studies. Table 1 presents flight condition at each case.

Table 1- Case studies

Study of Case	Speed (kt)	Weight (kg)	Altitude (ft)
1	60	2,200	4,000
2	80	2,200	4,000
3	100	2,200	4,000
4	60	2,200	10,000
5	100	2,200	10,000
6	60	1,900	4,000
7	100	1,900	4,000
8	60	2,500	4,000
9	100	2,500	4,000

From case 1 to 3 speed was changed from 60 to 100 kt. Cases 4, 6 and 8, perfomed at 60 kt, allow comparison with Stability and Control Derivatives of case 1. For Case 4 altitude has been changed from 4,000 ft to 10,000 ft, at Case 6. It is possible to compare case 1 to a low-weight condition flight, varying from 2,200 to 1,900 kg. In case 8, ther is also weight change, but now presenting a heavy condition of 2,500 kg. Similarly, Cases 5, 7, and 9 allow comparison with Case 3, at 100 kt. All flight data studied have been obtained from level flights performed under flight test rules. Stability and Control derivatives (SCD) identified for H-55 flight are presented in Tables 2 to 10, each one presenting one case studied.

Table 2 - Case Study Nr 1 H-55 helicopter; 60 kt Level Flight; 4.000 ft; 2200 kg

	u	w	q	v	p	r
X	-0,02494	0,02056	0,33652	0,00278	0,06924	-0,01219
Z	-0,06034	-0,77379	21,25270	0,00356	-0,02024	0,15582
M	0,02463	0,01364	-2,05335	-0,00092	-0,26629	0,00635
Y	-0,00039	-0,00626	0,07037	-0,10843	-0,45026	-21,32755
L`	-0,02991	0,03218	0,78405	-0,15219	-6,49507	0,18923
N`	-0,01004	0,00051	0,05867	0,06544	-0,66007	-0,78195

	ddc	ddb	dda	ddn
X	0,48910	-6,13237	1,05309	-0,00315
Z	-71,58945	-14,93226	0,08410	0,00076
M	3,71686	14,10604	-4,21761	0,00454
Y	-0,72276	-0,82412	1,44827	3,38374
L`	4,48838	-15,18504	-38,99614	3,06690
N`	1,74749	-2,65286	-8,55004	-7,62205

Table 3 - Case Study Nr 2 H-55 helicopter; 80 kt Level Flight; 4000 ft; 2200 kg

	u	W	q	v	p	r
X	-0,03118	0,01893	0,75314	0,00237	0,06987	-0,01405
Z	-0,02634	-0,84942	28,31778	0,00540	-0,05870	0,15454
M	0,02280	0,00745	-2,11812	-0,00103	-0,26629	0,00684
Y	0,00029	-0,00825	0,05466	-0,13163	-0,76420	-28,64937
L`	-0,02814	0,01804	0,79890	-0,15609	-6,42133	0,18598
N`	-0,00830	0,00063	0,09898	0,07277	-0,65911	-0,84480

	ddc	ddb	dda	Ddn
X	-0,13259	-6,08823	1,05328	-0,00344
Z	-78,56980	-22,11513	0,08411	-0,00008
M	5,69789	14,27670	-4,25491	0,00472
Y	-0,98364	-0,90009	1,30901	3,80328
L`	2,77426	-15,10829	-39,09486	3,37946
N`	1,77364	-2,42892	-8,37135	-8,53255

Table 4 - Case Study Nr 3 H-55 helicopter; 100 kt Level Flight; 4000 ft; 2200 kg

	u	w	q	v	p	r
X	-0,03771	0,01722	1,45377	0,00269	0,06277	-0,01573
Z	-0,00812	-0,90715	35,43191	0,00453	-0,06150	0,16902
M	0,02501	0,01250	-2,18671	-0,00100	-0,27743	0,00965
Y	0,00157	-0,01041	0,06188	-0,15513	-1,52085	-36,01247
L`	-0,02401	0,00498	0,81909	-0,15993	-6,35180	0,22345
N`	-0,00910	0,00485	0,06016	0,07551	-0,64914	-0,95196

	ddc	ddb	dda	Ddn
X	-0,81433	-6,12640	1,06615	-0,00393
Z	-84,71469	-28,38774	0,01043	0,00122
M	7,35920	14,62176	-4,32446	0,00677
Y	-1,22871	-1,00480	1,28747	4,14470
L`	1,17878	-15,42161	-39,37695	3,71142
N`	2,02035	-2,18805	-8,27515	-9,24600

Table 5 - Case Study Nr 4 H-55 helicopter; 60 kt Level Flight; 10000 ft; 2200 kg

	u	w	q	v	p	r
X	-0,02351	0,01181	0,43597	-0,00025	0,06688	-0,01098
Z	0,04170	-0,54095	24,34855	0,00295	-0,01313	0,15771
M	0,02556	0,00434	-2,07377	-0,00129	-0,26538	0,00267
Y	-0,00004	-0,00268	0,06622	-0,08497	-0,53984	-14,96937
L`	-0,05650	0,01931	0,71046	-0,14580	-8,11797	0,10640
N`	-0,01123	0,00041	-0,24156	0,04900	-1,20176	-0,62302

	ddc	ddb	dda	ddn
X	0,27206	-6,87217	1,05309	-0,00329
Z	-50,93934	-10,75547	-0,08410	0,00068
M	9,48179	14,55842	-642,28099	0,00462
Y	-0,41408	-0,76918	3,06741	2,50090
L`	-3,43642	-13,74342	-5,66990	2,26168
N`	2,16426	-2,31245	-0,96222	5,63151

Table 6 - Case Study Nr 5 H-55 helicopter; 100 kt Level Flight; 10000 ft; 2200 kg

	u	w	q	v	p	r
X	-0,03119	0,00862	1,99917	0,00184	-0,07029	-0,01491
Z	-0,00500	-0,61305	40,96593	0,00319	-0,03700	0,16254

M	0,02230	0,00430	-2,12684	-0,00180	-0,27819	0,00987
Y	0,00124	-0,00689	0,05803	-0,11949	-1,80347	-25,85601
L`	-0,01384	0,00344	0,74116	-0,15255	-7,89119	0,13888
N`	-0,00029	0,00393	0,01255	0,05420	-1,21098	-0,75500

	ddc	ddb	dda	ddn
X	-0,35478	-8,83193	1,06615	-0,00481
Z	-57,39188	-19,62293	0,00092	0,00042
M	-9,53351	15,97643	-5,04520	-0,12322
Y	-0,89434	-0,80384	1,29460	3,09740
L`	0,73108	-12,54973	-39,55142	2,79122
N`	2,32535	-2,01817	-8,27515	-6,89510

Table 7 - Case Study Nr 6 H-55 helicopter; 60 kt Level Flight; 4000 ft; 1900 kg

	u	w	q	v	p	r
X	-0,02964	0,02922	0,33942	0,00519	0,07780	-0,01284
Z	-0,18740	-0,95979	28,35418	0,00411	-0,02446	0,15342
M	0,02161	0,01938	-1,89670	-0,00067	-0,24661	0,00650
Y	-0,00081	-0,01029	0,08214	-0,13058	-0,45401	-26,68132
L`	-0,00665	0,04070	0,81426	-0,10804	-5,60146	0,16995
N`	-0,00670	0,00045	0,34824	0,07371	-0,56882	-0,82492

	ddc	ddb	dda	ddn
X	0,72652	-5,41703	0,46073	-0,00367
Z	-88,39322	-18,39379	-0,22426	0,00025
M	-2,19978	11,16557	-1,20503	0,00412
Y	-1,09167	-1,05762	1,45654	4,18119
L`	8,48584	-16,72277	-34,12607	2,80825
N`	1,47034	-2,40636	-8,22014	-8,14509

Table 8 - Case Study Nr 7 H-55 helicopter; 100 kt Level Flight; 4000 ft; 1900 kg

	u	w	q	v	p	r
X	-0,04715	0,02538	1,41825	0,00385	0,06548	-0,01717
Z	-0,01167	-1,12440	44,44071	0,00594	-0,07587	0,17511
M	0,02395	0,01720	-2,05854	-0,00050	-0,24347	0,00881
Y	0,00248	-0,01511	0,07376	-0,18846	-1,47513	-45,05213
L`	-0,03581	0,00590	0,89722	-0,10307	-5,25865	0,19904
N`	-0,01203	0,00342	0,11917	0,08218	-0,65165	-1,00884

X	-1,26138	-3,43005	1,11461	-0,00455
Z	-104,70699	-34,98466	0,01626	0,00137
M	20,73957	10,90181	-3,60372	0,01354
Y	-1,83702	-1,37126	1,28984	5,10994
L`	1,52408	-17,58536	-34,26510	3,39496
N`	2,11063	-1,52212	-7,67475	-9,86473

Table 9 - Case Study Nr 8 H-55 helicopter; 60 kt Level Flight; 4000 ft; 2500 kg

	u	w	q	v	p	r
X	-0,02341	0,01824	0,33726	0,00139	0,06231	-0,01301
Z	-0,02894	-0,63798	16,67792	0,00329	-0,01747	0,15470
M	0,02788	0,00744	-2,18762	-0,00123	-0,28897	0,00616
Y	-0,00019	-0,00391	0,06165	-0,09348	-0,44713	-17,56793
L`	-0,04542	0,02526	0,77412	-0,19605	-7,31546	0,20403
N`	-0,01285	0,00055	0,12694	0,06167	-0,73265	-0,73745

	ddc	ddb	dda	ddn
X	0,44019	-6,34636	1,11891	-0,00315
Z	-59,47065	-12,54363	-0,04205	0,00040
M	8,79910	17,10820	-4,82012	0,00462
Y	-0,45925	-0,81038	1,45929	2,83956
L`	0,98183	-15,95390	-44,16837	3,26243
N`	2,06271	-2,89937	-9,64973	-7,12882

Table 10 - Case Study Nr 9 H-55 helicopter; 100 kt Level Flight; 4000 ft; 2500 kg

	u	w	q	v	p	r
X	-0,03361	0,01372	1,49574	0,00222	0,05728	-0,01607
Z	-0,00673	-0,74053	30,95279	0,00372	-0,05019	0,16298
M	0,02576	0,00711	-2,27746	-0,00140	-0,30611	0,01021
Y	0,00124	-0,00795	0,05399	-0,13256	-1,54224	-29,73850
L`	-0,01872	0,00438	0,79280	-0,21543	-7,33120	0,24305
N`	-0,00440	0,00567	0,04609	0,06810	-0,68674	-0,89557

2	ddc	ddb	dda	ddn
X	-0,62801	-7,17193	0,77538	-0,00370
Z	-69,32814	-23,52980	-0,00982	0,00049
M	-5,93754	18,47073	-5,76595	-0,00271
Y	-1,11591	-0,85704	1,24701	3,48683
L`	0,98589	-14,87084	-44,45391	3,96079
N`	2,13747	-2,60935	-9,34544	-8,66732

From case 1 to 3, there was a velocity variation, respectively 60, 80 and 100 kt. Case 4 and 5 maintained level flight at 1000 ft at 60 and 100 kt. Case 7 and 8 show helicopter performance with low weight, at 1,900 kg

4. COMPARATIVE ANALYSIS

At Section 2, reliability of the methodology has been discussed. Unfortunately, no H-55 helicopter Control Derivative are available in literature, for comparison proposes. However, it is possible to to compare SCD H-55 behavior with those of a similar aircraft. The UH-1D (Hefley,1979) and BO-105 (Padfield, 2007) results has been selected for this propose, due to similarity of profile and weight of that rotorcraft. A comparison between UH-1D and H-55 is presented, for all nine flight conditions (Figures 2 to 5); considering that there are 60 SCD, for simplicity, only 9 has been shown. Additionally, a comparison among 3 aircraft over speed variation from 60 to 100 kt are presented. These 3 results are: BO-105 (Padfield, 2007); UH-1D (Hefley, 1979) and H-55 (Helimat identification).
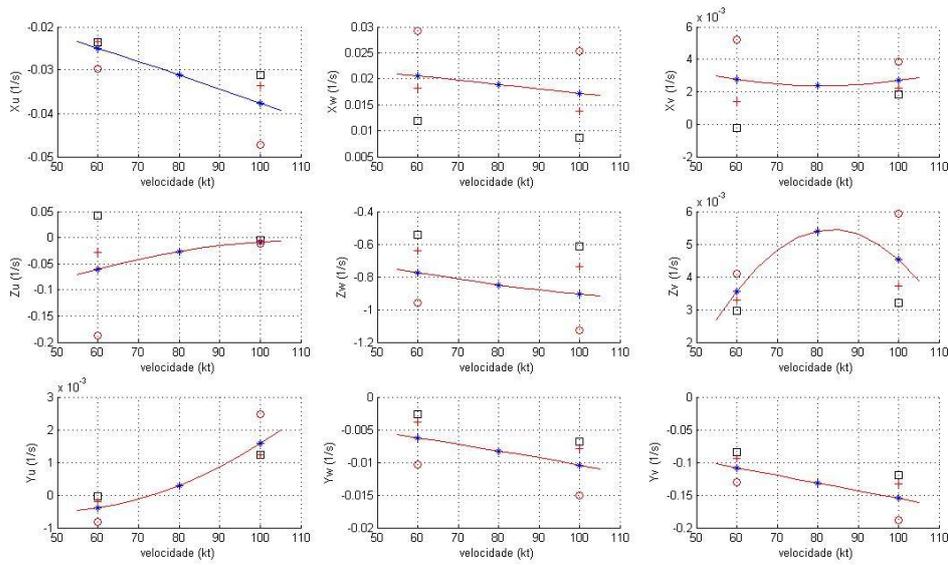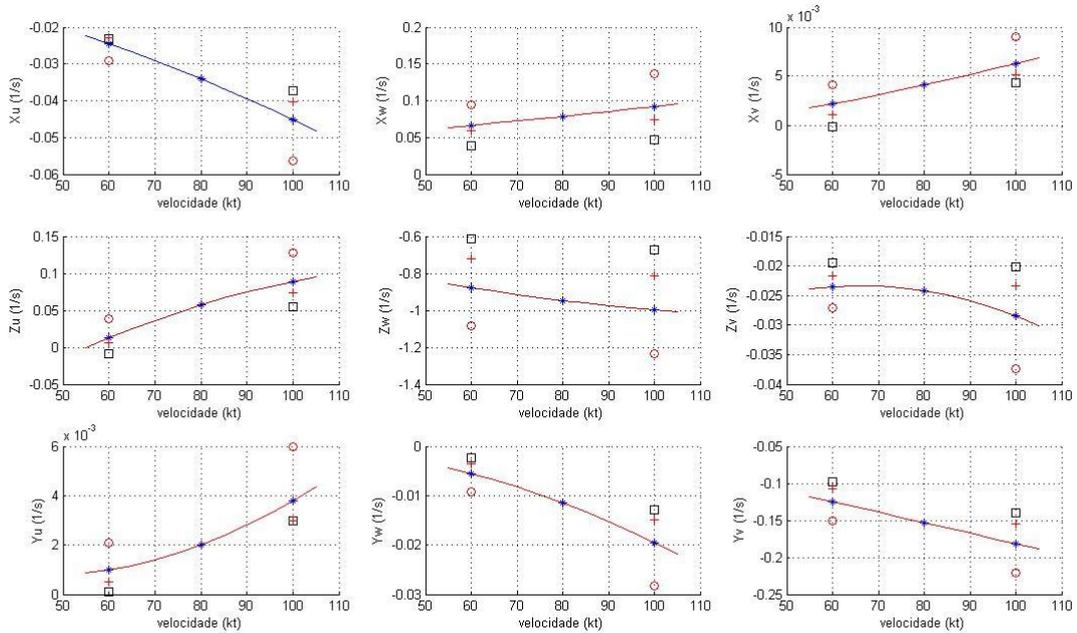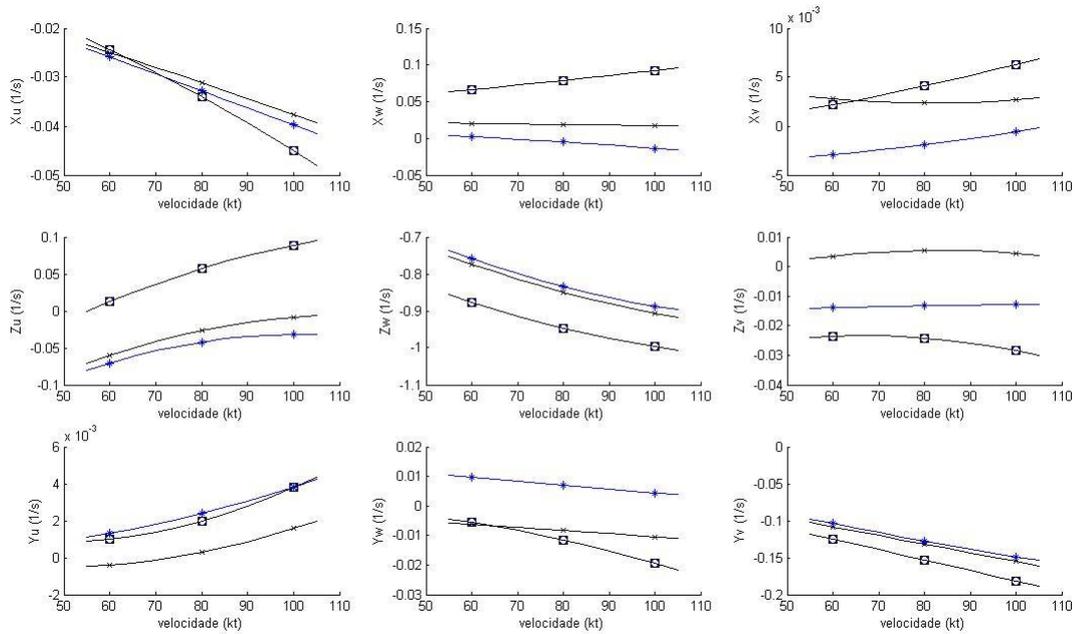
Figure 2 : Stability and Control Derivatives - Force and speed components - of H-55 Helicopter (Helimat Results)
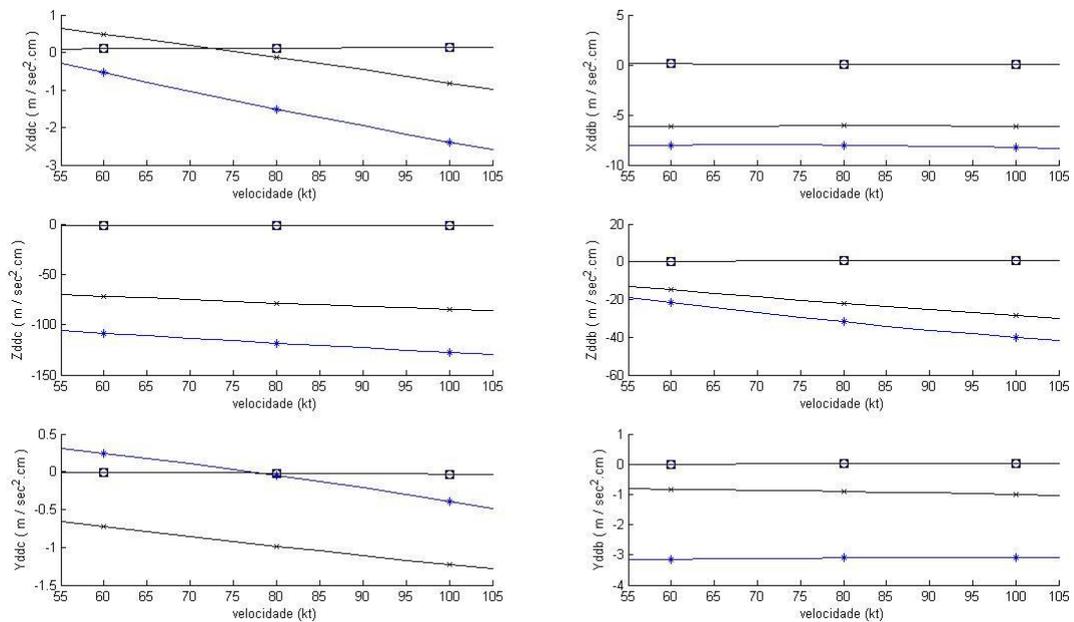*"o" high alttitude; "+" low-weigth; □ heavy*

Legend:

Figure 3 : Stability and Control Derivatives - Force and speed components - of UH-1D Helicopter (Hefley, 1979)
"o" high alttitude; "+" low-weigth; □ heavy

Legend:

Figure 4 : Stability and Control Derivatives - Force and speed components - of 3 different aircrafts
""BO-105 (Padfield, 2007); "x" UH-1D (Hefley, 1979); ◘H-55(Helimat)*

Legend:

Figure 5 : Stability and Control Derivatives - Force and speed components - of 3 different aircrafts
""BO-105 (Padfield, 2007); "x" UH-1D (Hefley, 1979); ◘H-55(Helimat)*

4.1 DISCUSSION

This work extends Cruz et al. (2009a) results, with Quad-m/CTa methodology. Cruz has performed system identification for flight test data successfully just for one flight condition, while this work presents nine conditions. All identification performed reached the criteria for acceptability: Cramer-Rao and Relative Correlation Coefficient criteria.

The nine flight condition studied allow comparison with literature results. First, it has been compared with Uh-1H identified SCD by Hefley (1979) in all nine different conditions. The results shown similar tendencies for SCD evaluation among speed, altitude and weight variation. Also the magnitude of each SCD are very similar for helicopter models analyzed:.BO-105 (Padfield, 2007); UH-1D (Hefley, 1979) and H-55 (Helimat identification).

5. ACKNOWLEDGEMENTS

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