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Statistical Analysis in the Aerodynamic Forces and Moments Measurement in Indonesian Low-Speed Wind Tunnel

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Abstract**: *The reliability of measurement should be based on accuracy and precision. A reliable measurement system will deliver quality results of data. Quality of the data will affect the decision which taken based on analysis of the data. A decision taken based on poor quality data will lead to a misleading action. This paper presents application statistical analysis in the aerodynamics measurement system in Indonesian Low-Speed wind Tunnel (ILST), using case of repeatability data on testing of Unmanned Aircraft Vehicle (UAV) model, in terms of one-way and two-way analysis of variance. The aerodynamics measurement system could be considered to accept statistically. The calculation was performed ratio of F to P using One-ways Analysis of Variance (ANOVA) methods indicate almost equal to zero. In case data is small we used Two-way ANOVA analysis show the variance also very small. That calculation results showed the measurement system can be categorized as an acceptable and proper measurement.***

Keywords**: *Statistical analysis, ANOVA, quality, repeatability, acceptable measurement.***

I. INTRODUCTION

Design cycle of an aircraft prototype up to the manufacture consist of several phases of the process. The first step we studied aerodynamics characteristics by using numerical simulation i.e. Computational Fluid Dynamics software. And then we do aerodynamics testing using an aircraft model in a wind tunnel, which is intended to acquire aerodynamics characteristics of an aircraft. After we found the optimal of freeze model of an aircraft the first prototype could be manufactured.

Test facility in ILST is equipped with a measuring device called External Balance. It can measure three components forces and three moments simultaneously. They are used to describe the aerodynamic performance of an aircraft, namely: Lift, Drag, Pitching Moment, Side Force, Yawing Moment, and Rolling Moment. The External Balance consists of six load cells which are positioned in such a way that the value for each component is obtained from the combination of all load cells readings. Hence, there is no one single component can be deduced from one load cell reading only.

The aerodynamics measurement systems in the wind tunnel must have high quality and highly reliable. Unfortunately, the quality of such measurements is merely based on visual observation of the graphs created from aerodynamic forces and moments obtained from the measurement and not based on the quantitative measure. This method is certainly debatable and prone to error however the error measurement should quantifications due to the good experiment approach [1].

When faced with a situation of having to make the right decision from the available options, we need the previously obtained information to support the decision making. This information may come from the measurement results, research outputs, or other sources. Regardless of the sources, data quality has to be considered, because it will affect the result or action taken as a consequence of the selected option.

A decision taken based on poor quality data will lead to a misleading action. Therefore, the data used as a basis for decision making must be of good quality. To get good quality data, surely a measurement system that generates such data, in addition to being reliable, it also has to be measurable. The reliability of a measurement system can be seen from its accuracy and precision. Accuracy indicates deviations from average values, while precision demonstrates the ability to provide repeatable measurement results under similar measurement conditions.

II. WIND TUNNEL TESTING

Aircraft flight mission is generally contained of take-off, ascending, cruise, descending and landing [2] and those missions were done for both commercial aircraft and UAV. Takeoff and landing are a cycle aspect during flight and to do safely it needs enough lifting force and for landing situation, it also needs drag force. That aerodynamics characteristic could be known by putting an aircraft or UAV model to the wind tunnel testing (WTT). The WTT arrangement and result will be explained including some condition described in the following chapter;

A. Indonesian Low-Speed Wind Tunnel

Testing was conducted using an Indonesian Low-Speed wind Tunnel (ILST). ILST is "closed-circuit wind tunnel" which has a test section with a cross-section of 3 m x 4 m, length 10 m, pressurized atmosphere and a maximum wind speed of 110 m / s with Mach number 0.3. The test section of the wind tunnel is equipped with two upper and lower turntables with a diameter of 3 m that move in sync. The turntable can be rotated up to ± 90 degrees. The wind tunnel is equipped with three layers of honeycomb and fine turbulence screen.

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The variation of wind speed in the test section is less than 0.2% of the average value. Static pressure variations in the flow direction within ± 0.3% of the dynamic pressure at a speed of 70 m / s. Flow angularity ± 0.1 degrees of pitch and ± 0.2 degrees for yaw angle.

The final section of the test section is slightly larger, the inclination of the crossing axis of about 2 degrees to maintain the liquid deviation in the test section as small as possible. The boundary layer around the test section wall has a thickness of about 11 cm on the left and right side, and 13 cm on the floor and ceiling. Thus the blockage area of the test section is 90% of the cross-section area of the test section. Diagrammatic of ILST shows in figure 1.

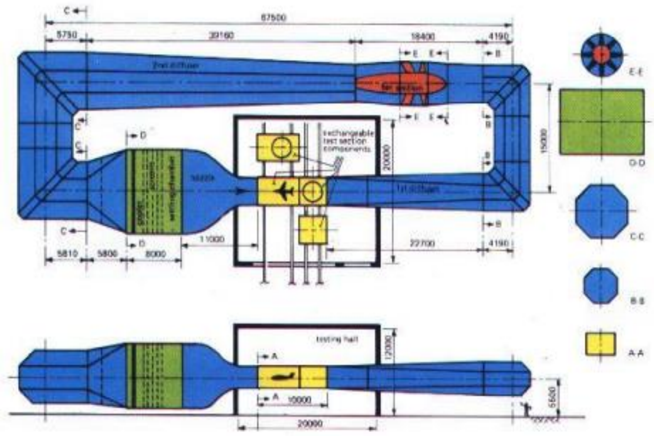

Figure 1. Indonesian Low-Speed wind Tunnel Diagram

External balance to support the test model and is located above the test section, has a T-shaped platform type, which is connected to the "earth-frame" through 6 load cell (Q1 s / d Q6)."Earth-frame", the platform and the model can be driven rotating about a vertical axis, as well as the upper and lower turntable. The sixth load cell connected to LLI (Low-Level Interface) to measure the force. Results by the load cell force measurements can be derived and obtained the calculation of aerodynamic forces and moments that occur in the balance centre. External balance has a capacity for forces and moments measurement in the ILST shows in table 1.

Table 1. The maximum load of the external balance component

No.		Components	Max Loads [N] or [Nm]	Absolute Accuracy	
				[% FS]	[N] or [Nm]
1	K1	*Lift*	17500	0.02	3.5
2	K2	*Drag*	3500	0.02	0.7
3	K3	*Pitching Moment*	3750	0.03	1.125
4	K4	*Side Force*	3500	0.02	0.7
5	K5	*Yawing Moment*	3250	0.02	0.65
6	K6	*Rolling Moment*	3000	0.04	1.2

Furthermore, the maximum allowable error calculated by the equation (1)[3]

$$E_i = \left(0.3 + 0.7\frac{P_i}{P_{i\max}}\right)0.001\, f P_{i\max} \qquad (1)$$

Where,

Ei : The maximum allowable error.

P_i : The force or moment on the *Ki*th component.

$P_{i\max}$: The maximum capacity of the K*i*th component.

f : A factor, which depends on the force component.

B. Measurement Technic

Methods of measuring aerodynamic force and moment of the aircraft or UAV model in the wind tunnel by using External Balance shown in figure 2 [3],[4]. And then Layout or scheme of External Balance in ILST shown in Figure 3, there is six value of a load cell to measure the forces and moments i.e. lift, drag, pitching moment, side force, rolling moment, and yawing moments.

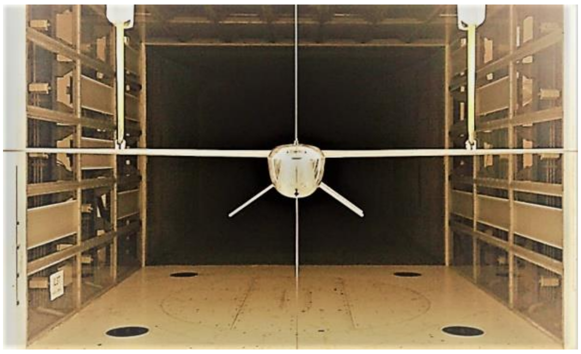

Figure 2. UAV model installed in the test section

ILST External Balance comprises a T-shaped platform that is connected with six load cells that measure aerodynamic forces and moments. Data from the load cell is connected to a device called Low-Level Interface (LLI). Data obtained by the forces and moments to the centre at the centre of balance. Furthermore, the data can be processed to be defined at the desired point.

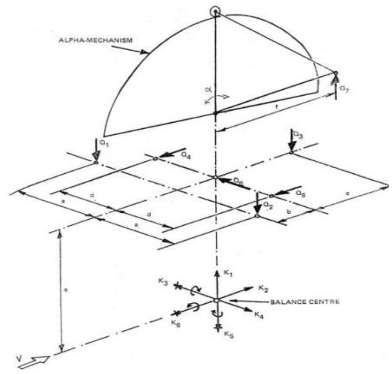

Figure 3. Lay-Out of External Balance with Load Cells (Q1 up to Q6)

C. Forces and Moment aerodynamics

The measurement characteristic aerodynamic of aircraft or UAV test model in the wind tunnel measure three forces components i.e. lifts (L = lift), Drag (D = drag), Side Force (SF = side forces) and three components moments are pitching moment (MP = pitch moment), a rolling moment (MR = rolling moment), and yawing moment (M_{Yaw} = yaw moment) [5].

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The six components of forces and moments can be formulated as follows:

Three component forces:

$$L = \frac{1}{2}\rho V^2 S C_L$$
(2)

$$D = \frac{1}{2}\rho V^2 S C_D$$
(3)

$$S_F = \frac{1}{2}\rho V^2 S C_Y$$
(4)

Three component moments:

$$M_P = \frac{1}{2}\rho V^2 S C_m$$
(6)

$$M_R = \frac{1}{2}\rho V^2 S C_l$$
(7)

$$M_{Yaw} = \frac{1}{2}\rho V^2 S C_n$$
(8)

Where ρ: air density, V: free stream velocity, S: reference area, C_L: Lift Coefficient C_m: Pitch Moment Coefficient, C_D: Drag Coefficient, C_Y: Side Force Coefficient, C_l: Rolling Moment Coefficient, C_n: Yawing Moment Coefficient.

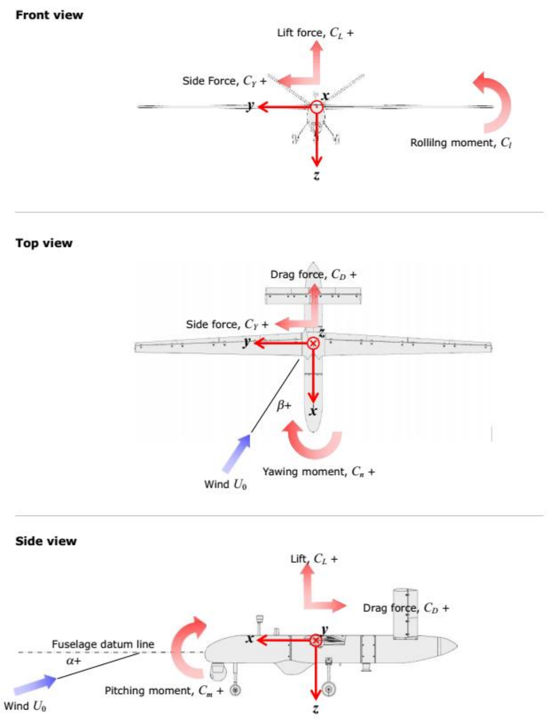

Figure 4. Convention magnitude, Sign and direction forces and moments

All of the aerodynamic force and moment measured by load cell correlated with the appropriate position in the external balance. Offset small geometry and strain and friction gives the deviation coefficient of the actual value. Therefore the forces and moments obtained from the measurement results, in software multiplied by the coefficient matrix external balance calibration. The relationship between the aerodynamic forces and moments in units of measurement and raw data matrix shown in the following equation:

$$[K_i] = [a_{ij}] \cdot [R_i]$$
(9)

Where: K_i : Forces or moments

a_{ij} : External Balance Calibration Coefficient

R_i : Raw data

Forces and moments of the measurement results are normalized to the dynamic pressure, a reference area of wings, and the mean aerodynamic chord. Agreements signs and directions to all the coefficients shown in Figure 4 where CL, CD, CY, C_m, C_l, C_n are the coefficient of lift, drag, side force, a moment of the pitch, rolling moment, and the yawing moment respectively.

III. RESULT AND DISCUSSION

In order to use statistic application, three experiment data of The WTT were conducted. The running investigation is written in table 2. And any typical experimental data record shows in table 3.

Table 2. Running list for statistics data investigation

No	RUN	configuration	V(m/s)	AOA	Beta
1	Exp 1	Wing Body	65	A	0
2	Exp 2	Wing Body	65	A	0
3	Exp 3	Wing Body	65	A	0

Table 3. Experimental Result of WTT Run No 1 (Exp 1)

ALPHA	BETA	CL	CD	CM25	CY	CYAW	CROLL
-9.02	0	-0.3376	0.1332	-0.1896	0.0015	0	-0.0034
-8	0	-0.3219	0.1072	-0.226	0.0005	-0.0004	-0.0044
-7	0	-0.2596	0.0751	-0.2302	0	-0.0003	-0.0035
-6	0	-0.1546	0.0483	-0.2321	0.0001	-0.0003	-0.002
-4	0	0.0303	0.0348	-0.2172	-0.0021	-0.0002	0.0006
-2.01	0	0.2468	0.0301	-0.1729	-0.0037	-0.0002	-0.0009
0	0	0.468	0.03	-0.2039	-0.0037	-0.0001	-0.0008
2.01	0	0.6848	0.0327	-0.1443	-0.0048	-0.0003	0.0013
4	0	0.8973	0.0383	-0.0928	-0.0052	-0.0002	0.0005
6.01	0	1.095	0.0456	-0.0639	-0.0062	-0.0003	0.0018
7	0	1.1857	0.0493	-0.0401	-0.0063	-0.0002	0.002
8.01	0	1.2295	0.0567	-0.0209	-0.0063	-0.0005	0.0025
9.01	0	1.2522	0.0664	0.0073	-0.0064	-0.0004	0.0036
10.01	0	1.2955	0.0752	0.0414	-0.0069	-0.0004	0.0015
11	0	1.3358	0.0835	0.061	-0.0069	-0.0004	0.0024
12	0	1.381	0.0946	0.1023	-0.0074	-0.0003	0.0026
13.01	0	1.4033	0.1099	0.1105	-0.0068	-0.0004	0.0029
14	0	1.4156	0.1255	0.0891	-0.0073	-0.0003	0.0012

Three sets of experimental data result i.e. Exp 1, Exp 2 and Exp 3 can be obtained. Graphic Plots of three sets of the experimental data result shown in figure 5 up to figure 10.

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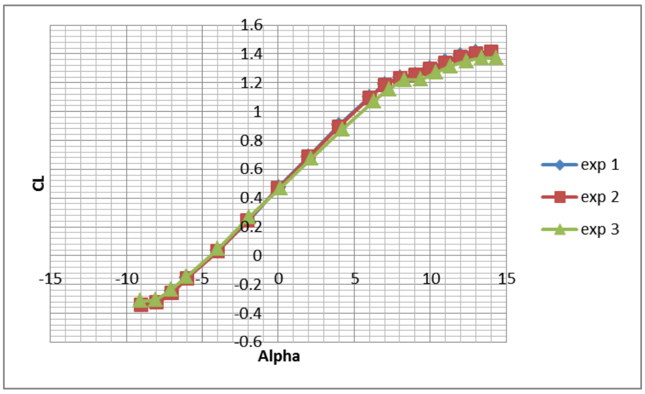

Figure 5. Graph of CL vs. Alpha

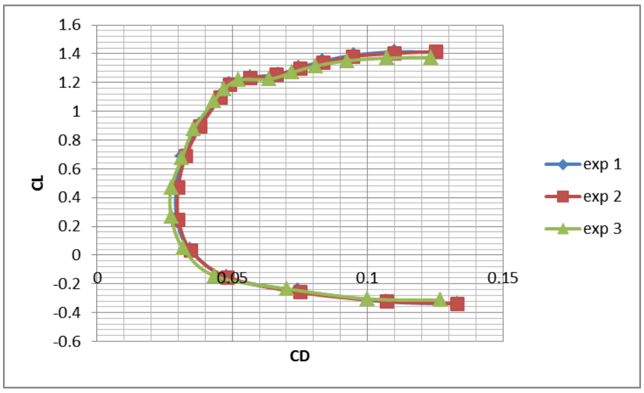

Figure 6. Graph of CL vs. CD

Table 4. One-way ANOVA Table for CL three set of data

Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	17	11.4315	0.672441	0.450032		
Column 2	17	11.5219	0.677759	0.4533		
Column 3	17	11.3135	0.6655	0.423335		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.001285	2	0.000642	0.001453	0.998548	3.190727
Within Groups	21.22667	48	0.442222			
Total	21.22796	50				

Table 5. Two-way ANOVA Table for CL three set of data

Anova: Two-Factor Without Replication						
SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
Row 1	3	-0.9884	-0.32947	0.000198		
Row 2	3	-0.9508	-0.31693	0.000108		
Row 3	3	-0.7427	-0.24757	0.000149		
Row 4	3	-0.4547	-0.15157	2.1E-05		
Row 5	3	0.1161	0.0387	7.06E-05		
Row 6	3	0.7547	0.251567	0.000214		
Row 7	3	1.4098	0.469933	1.3E-05		
Row 8	3	2.0485	0.682833	4.71E-05		
Row 9	3	2.6821	0.894033	0.000233		
Row 10	3	3.2675	1.089167	0.000226		
Row 11	3	3.531	1.177	0.000299		
Row 12	3	3.6835	1.227833	8.67E-05		
Row 13	3	3.7316	1.243867	0.000344		
Row 14	3	3.8682	1.2894	0.000289		
Row 15	3	4	1.333333	0.000261		
Row 16	3	4.1226	1.3742	0.000411		
Row 17	3	4.1879	1.395967	0.000516		
Column 1	17	11.4315	0.672441	0.450032		
Column 2	17	11.5219	0.677759	0.4533		
Column 3	17	11.3135	0.6655	0.423335		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	21.22099	16	1.326312	7463.415	1.72E-52	1.971683
Columns	0.001285	2	0.000642	3.615017	0.038415	3.294537
Error	0.005687	32	0.000178			
Total	21.22796	50				

Figure 4 shows graphic plot CL vs. Alpha and One way ANOVA table of CL can be sawed in table 4.

Table 6. One-way ANOVA Table for CD

Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	18	1.2364	0.068689	0.00114		
Column 2	18	1.2302	0.068344	0.001149		
Column 3	18	1.1769	0.065383	0.001099		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000119	2	5.94E-05	0.052642	0.948771	3.178799
Within Groups	0.057587	51	0.001129			
Total	0.057705	53				

Table 7. Two-way ANOVA Table for CD

Anova: Two-Factor Without Replication				
SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	0.3931	0.131033	1.34E-05
Row 2	3	0.3141	0.1047	1.59E-05
Row 3	3	0.2195	0.073167	6.41E-06
Row 4	3	0.1398	0.0466	6.79E-06
Row 5	3	0.1009	0.033633	2.58E-06
Row 6	3	0.0871	0.029033	2.06E-06
Row 7	3	0.0867	0.0289	1.81E-06
Row 8	3	0.0957	0.0319	4.9E-07
Row 9	3	0.1118	0.037267	1.9E-06
Row 10	3	0.1343	0.044767	1.84E-06
Row 11	3	0.1452	0.0484	1.33E-06
Row 12	3	0.1658	0.055267	6.6E-06
Row 13	3	0.1968	0.0656	3.37E-06
Row 14	3	0.2219	0.073967	2.7E-06
Row 15	3	0.2478	0.0826	2.17E-06
Row 16	3	0.2819	0.093967	1.62E-06
Row 17	3	0.3271	0.109033	2.52E-06
Row 18	3	0.374	0.124667	9.43E-07
Column 1	18	1.2364	0.068689	0.00114
Column 2	18	1.2302	0.068344	0.001149
Column 3	18	1.1769	0.065383	0.001099

Based on the One-way ANOVA table 4, the value F is small and value P almost 1 that is mean no differences between Exp to Exp. Furthermore from table 5; Two-way ANOVA shows if the value F is big enough so the P value is very small. The order of variance is so small i.e. 8.76E-05 up to 0.000298 so no significant difference means between column to column are guaranteed.

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Table 7. Two-way ANOVA Table for CD (continued)

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.057556	17	0.003386	3817.724	1.03E-50	1.933207
Columns	0.000119	2	5.94E-05	67.02587	1.59E-12	3.275898
Error	3.02E-05	34	8.87E-07			
Total	0.057705	53				

Also the One-way ANOVA for the three set CD result table 6 and Two-way ANOVA table 7. F value One-way ANOVA is small 0.05246 and P value is 0.948711 almost 1 that is mean no significant difference between Exp to Exp. As a result of the Two-way ANOVA coefficient CL the value F is big enough so the P value is very small. The order of variance is so small i.e. 4.9E-07 up to 6.41E-05 so no significant difference means between column to column are guaranteed..

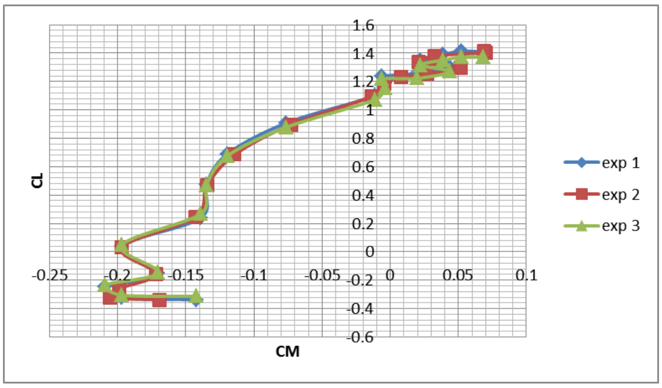

Figure 7. Graph of CL vs. CM

Table 8. One way ANOVA Table for CM

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	18	-1.14754	-0.06375	0.010466		
Column 2	18	-1.0658	-0.05921	0.010204		
Column 3	18	-1.1624	-0.06458	0.009741		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000301	2	0.00015	0.014828	0.985286	3.178799
Within Groups	0.516995	51	0.010137			
Total	0.517296	53				

Furthermore, figure 7 is the graphical plot of CL vs. CM. The ANOVA analysis of the three set CM data shows in table 8 for One-way ANOVA and table 9 for Two-way ANOVA. Such the result ANOVA for CL and CD, a similar result also obtained for One-way and Two-way ANOVA of CM.

F value One-way ANOVA is small 0.014828 and P value is 0.985286 this is almost 1 that is mean no significant difference between Exp to Exp. As a result of the Two-way ANOVA coefficient CL the value F is big enough so the P value is very small. The order of variance is so small i.e. 4.9E-07 up to 6.41E-05 so no significant difference means between column to column.

Table 9. Two way ANOVA Table for CM

Anova: Two-Factor Without Replication						
SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
Row 1	3	-0.4731	-0.1577	0.000194		
Row 2	3	-0.5949	-0.1983	5.32E-05		
Row 3	3	-0.6017	-0.20057	6.62E-05		
Row 4	3	-0.5187	-0.1729	8.32E-06		
Row 5	3	-0.5682	-0.1894	0.00018		
Row 6	3	-0.425	-0.14167	4.94E-06		
Row 7	3	-0.412	-0.13733	2.01E-05		
Row 8	3	-0.347	-0.11567	1.26E-05		
Row 9	3	-0.2049	-0.0683	0.000124		
Row 10	3	-0.0408	-0.0136	4.69E-06		
Row 11	3	-0.0102	-0.0034	9.3E-07		
Row 12	3	0.00751	0.002503	5.44E-05		
Row 13	3	0.0726	0.0242	1.59E-05		
Row 14	3	0.1529	0.050967	5.13E-05		
Row 15	3	0.0675	0.0225	2.41E-06		
Row 16	3	0.1077	0.0359	1.07E-05		
Row 17	3	0.17685	0.05895	9.3E-05		
Row 18	3	0.2357	0.078567	0.000283		
Column 1	18	-1.14754	-0.06375	0.010466		
Column 2	18	-1.0658	-0.05921	0.010204		
Column 3	18	-1.1624	-0.06458	0.009741		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.514935	17	0.03029	499.9718	9.66E-36	1.933207
Columns	0.000301	2	0.00015	2.481067	0.098677	3.275898
Error	0.00206	34	6.06E-05			
Total	0.517296	53				

In the case of CY, CYaw and CRoll we obtained the value so small from the WTT data result. Based on our experience the small model like UAV the range value of CY, CYaw and CRoll is small and sensitive see also [6]. Whether the moderate size of an aircraft model has un-sensitive characteristic data on CY, CYaw and CRoll. The ratio of struts and wing chord of model relative big enough one of the cause of the sensitivity. The next chance the author will be studied the sensitivity and we take the data three times in the almost same time. In the other hand because of the taken data in these case indifference condition. Exp 1 and Exp 2 take in the 2018 but Exp 3 in 2016. We do not have really the same condition among Exp1, Exp 2 and Exp 3.

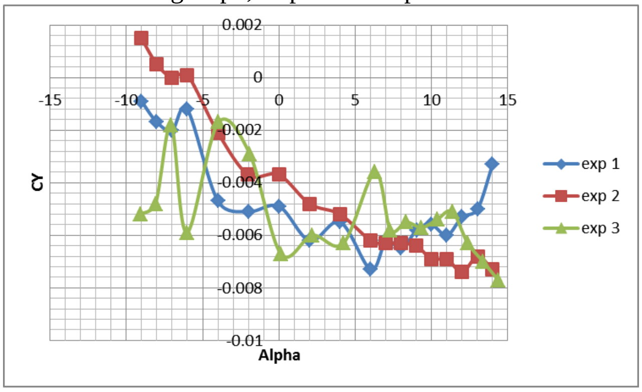

Figure 8. Graph of CY vs. Alpha

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Figure 8 show graph CY vs. Alpha and the One-way ANOVA Result of the three set CY data shows in table 11. The value F for the One-way ANOVA for CY equal to 0.656816 while the P value is 0.52283. We can not make a conclusion of this result. So we need to see the variance of the CY data result.

Table 11. One-way ANOVA Table for CY

Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Column 1	18	-0.0779	-0.00433	9.15E-06		
Column 2	18	-0.0832	-0.00462	3.78E-06		
Column 3	18	-0.0934	-0.00519	2.82E-06		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.9E-06	2	3.45E-06	0.656816	0.52283	3.178799
Within Groups	0.000268	51	5.25E-06			
Total	0.000275	53				

Table 12 shows the Two-way ANOVA for CY. The average each row of CY are -0,00633 up to -0,00127 and the order of variance data start from 1.15E-05 up to 5,92E-06. From point of view, the variance value is small that means the differences between column not significant.

Table 12. Two-way ANOVA Table for CY

Anova: Two-Factor Without Replication						
SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
Row 1	3	-0.0046	-0.00153	1.15E-05		
Row 2	3	-0.006	-0.002	7.09E-06		
Row 3	3	-0.0038	-0.00127	1.21E-06		
Row 4	3	-0.007	-0.00233	9.96E-06		
Row 5	3	-0.0085	-0.00283	2.65E-06		
Row 6	3	-0.0117	-0.0039	1.24E-06		
Row 7	3	-0.0153	-0.0051	2.28E-06		
Row 8	3	-0.017	-0.00567	5.73E-07		
Row 9	3	-0.017	-0.00567	3.23E-07		
Row 10	3	-0.0171	-0.0057	3.61E-06		
Row 11	3	-0.0183	-0.0061	7E-08		
Row 12	3	-0.0183	-0.0061	2.8E-07		
Row 13	3	-0.0179	-0.00597	1.43E-07		
Row 14	3	-0.0179	-0.00597	6.63E-07		
Row 15	3	-0.018	-0.006	8.1E-07		
Row 16	3	-0.019	-0.00633	1.1E-06		
Row 17	3	-0.0188	-0.00627	1.21E-06		
Row 18	3	-0.0183	-0.0061	5.92E-06		
Column 1	18	-0.0779	-0.00433	9.15E-06		
Column 2	18	-0.0832	-0.00462	3.78E-06		
Column 3	18	-0.0934	-0.00519	2.82E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.000173	17	1.02E-05	3.669093	0.000614	1.933207
Columns	6.9E-06	2	3.45E-06	1.241184	0.301808	3.275898
Error	9.45E-05	34	2.78E-06			
Total	0.000275	53				

The graphic plot of CYaw vs Alpha can be sawed in figure 9. The graph of CY, CYaw and CRoll are fluctuating because the value CY, CYaw and CRoll are small and very sensitive.

So the One-way and Two-way Result for CYaw and CRoll are very similar to the One-way and Two-way Result for CY.

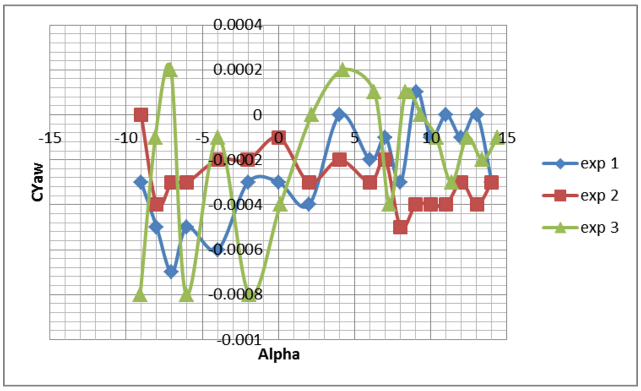

Figure 9. Graph of CYaw vs. Alpha

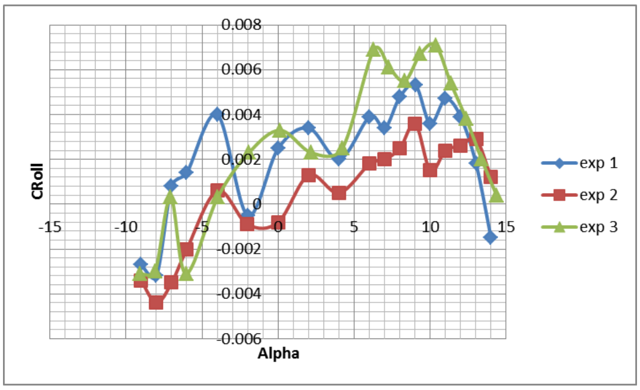

Figure 10. Graph of CRoll vs. Alpha

IV. CONCLUSION

One-way ANOVA for CL, CD and CM provide the value F is small and P almost one. That indicates no significant difference between Exp to Exp. Furthermore the Two-way ANOVA the variance of three set of data CL, CD and CM are small. In the other hand the value of F is big with P almost zero, therefore, that is the fact negligible between Exp to Exp.

A study to the application of One-way and Two-way ANOVA on the aerodynamics ILST WTT was performed good result although we still need to try taken some data in the same time to confirm good quality for UAV WTT. In the near future, we would like to use ANOVA on the commuter aircraft and the other WTT data result

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