Improving the accuracy of Taylor's wind tunnel measurements

Hutomo Wibowo, Abdulkareem Sh. Mahdi Al-Obaidi
School of Engineering, Taylors University, Malaysia

Abdulkareem.Mahdi@taylors.edu.my

Abstract
This paper aims to improve the accuracy of Taylor's wind tunnel measurement. During the operations of the Taylor's wind tunnel, it was found that the wind tunnel has slight deviation in the measurement in terms of the lift and drag measurement. The study focused on the quantification of the wind tunnel sources of errors experimentally. 4 different experiments were considered identify the errors under 4 parameters which are the effect of air leak, flowrate, test rig and size of the model in the wind tunnel. Based on the experiments, the contribution of the errors percentages is quantified as 1.23%, 0.65%, 24.87%, and 20.18% respectively. the results obtained from the experiments are compared with the published paper. Errors contributed by the air leak and flowrate can be corrected by including the percentage error contribution during the experiment as tolerance values that can either be subtracted from the results. For test rig, the error contribution can be corrected by implementing the Eq. (1) to obtain the true drag and lift coefficient. Lastly the error contributed by the size of the model can be minimized. The percentage error contribution in the wind tunnel can be further identified by conducting other experiments involving the drag and lift such as the effect of angle of attack on the drag and lift measurement of NACA 0012 in the wind tunnel, the effect of shapes on the drag and lift measurement in the wind tunnel, the effect of lab conditions in the wind tunnel, the effect of rigidity of the connections of test rig with the load cell

Keywords: Experimental, Wind tunnel, sources of error, Drag, lift,

1.0 Introduction

Taylor's wind tunnel is an open-section wind tunnel that was initially created by former student of Taylor's University located in Malaysia. Taylor's wind tunnel is built for education and research purposes. A number of students have used the wind tunnel for different purposes. Taylor's wind tunnel specifications can be referred to S. Eftekhari, [1].

Wind tunnel is a useful tool to study the aerodynamic characteristics of different objects with various shapes and sizes. The accuracy of the subsonic wind tunnel which is located in Taylor's University laboratory will have a great impact on the understanding of aerodynamic and fluid mechanics. Methodology is conceived based on the DOE approach [2], these errors are then classified in 3 different categories. However, it is important to determine the potential error sources in the wind tunnel to improve the data accuracy of the wind tunnel. This paper has listed several experiments that was conducted and validated to determine the potential error sources in the wind tunnel.

According to the study of the summary of experimental uncertainty, Stern, et al. [2] pointed out that in experiments, the true values of measured variables are usually difficult to be determined since experiments tends to always have errors given by the instrumentations, facility data acquisition and environmental and data acquisition and reduction limitations. Mills and Chang [3], also pointed out that physical quantities such as velocity, flowrate, temperature that are measured in experiment are subject to errors. There are 2 types of errors. these errors are precision errors and bias errors.

Precision errors can be called random errors which can be associated with instruments such as hot wire probe which is used to measure various parameters such as velocity, flowrate and temperature. According to Mills and Chang [3], precision errors can be treated through statistical analysis. On the other hand, bias errors can also be called systematic errors which can be associated with calibration error such as zero-offset errors for example zero-offset error of Vernier caliper which causes a constant absolute error in all the readings [3]. However, accuracy is defined on how close is the measured value to the true value and is usually in terms of percentage errors. Accuracy increases as errors approaches zero [2].

According to Lombardi et al. [4], stated that the wall interference effect in the wind tunnel test section is considered to be one of the main sources of error that affects the accuracy of the results. They conducted a study of correction of the wall interference effects in wind tunnel experiments numerically under two conditions. Free air flow over the model and measured pressure values over the wind tunnel walls are used as boundary conditions.

Rhode and Oberkampf [5], conducted a study of estimation of uncertainties for a model validation experiment in a wind tunnel. The author studied the source of uncertainties in the wind tunnel by implementing DOE strategy in order to categorized the error sources into 3 classes which are

- Random uncertainty
- Flow field non-uniformity uncertainty
- Model and instrumentation uncertainty

The author concluded that the major contributor to the uncertainty in wind tunnel falls under the flow field non-uniformity to the total uncertainty.

S. Lai, [6] performed a study in the effect of size and shape of side mirrors on the drag of a personal vehicle. The study focuses to calculate the drag contributions of the side mirrors. The author demonstrates a calculation formula to calculate the coefficient of drag in Taylor's University wind tunnel since the results obtained from the wind tunnel is in drag force. Therefore, Eq. (1) was developed to estimate the coefficient of drag of the model only.

$$C_{D(model)} = C_{D(total)} \frac{S_{total}}{S_{ref}} - C_{D(Rod)} \frac{S_{Rig}}{S_{ref}} \tag{1}$$

where,

- $C_{D(Model)}$ is the coefficient of drag of the model.
- $C_{D(total)}$ is the total coefficient of drag.
- S_{total} , which is the total frontal area of the model and test rig.
- S_{ref} is the frontal area of the model without the test rig.
- $C_{D(rig)}$ is the coefficient of the test rig.
- S_{rig} frontal area of the test rig.

This project was offered for the final year project in Taylor's University. The purpose of this project is to quantify the sources of error that can be identified in the Taylor's wind tunnel and if possible propose and engineering solutions to improve the wind tunnel. In this paper, there are four effects that are considered to determine the error sources such as:

- The first is the effect of the air leak on the velocity of the wind tunnel test section. This test is to assess the wind tunnel flow quality due to holes since flow quality may affects the wind tunnel results, accuracy [7].
- The second is the effect of the flowrate in the test section at different frequency ranging from 0 to 40 Hz. This study is to ensure that the accuracy of the flowrate at different frequency from the theoretical calculation wind tunnel flowrate. By knowing the difference, the experimenter will be able to make a correction in order to run at a desired speed and flowrate by taking into the consideration of the difference.
- The third is the effect of test rig/support system of the model on the drag and lift measurement. The study of the test rig interference is very important among the aerodynamic testing due to it adverse effects that it brings to the results [8]. The effect of the test rig can be calculated using Eq. (1) from the study conducted by S. Lai [6]
- The fourth is the study of the effect of the size of the model on the drag and lift measurement [9,10]. The present paper aims to to identify what are the sources

of errors in measuring the aerodynamic characteristics and analyze and assess the contribution of each error source. The project is limited at low subsonic speed in the range of 0 m/s to 38 m/s and at 5 different angle of attack range from 0 to 20 at the interval of 5 degrees. Errors sources is also limited under 3 different categories and human errors are not included. As for the model, NACA 0012 Finite wings airfoil will be used.

2.0 Research Methodology

The sources of error are identified through the observations of doing the experiments in Taylor's wind tunnel. The errors are then classified under 3 different categories which are the instrumental errors, environmental errors and test rig errors. 10 different sub-categories are conceived and 4 different sub-categories which are the effect of air leakage, effect of the support, effect of the flowrate and lastly effect of size of the model.

2.1 Data Extraction

All of the published paper data were extracted using the WebPlotDigitizer v3.12 that is able to automatically follow and acquire data points from a given high resolution image of C_D-AOA or C_L-AOA curve, to extract the digitized drag and lift coefficient at different AOA information (refer to Figure 6). Before obtaining the Published data [20], the two axis limits are initially set. Then, individual data points were selectively chosen. The accumulated data is compiled in the excel spreadsheets. The procedure was conducted three times to take the average. Once the average extracted data have been compiled, the author performed interpolations for the desired data points such as angle of attack of 0, 5, 10, 15, and 20 from the extracted data. After the desired data has been acquired, the author can finally conduct a comparison with the experimental data obtained from the TUWT.

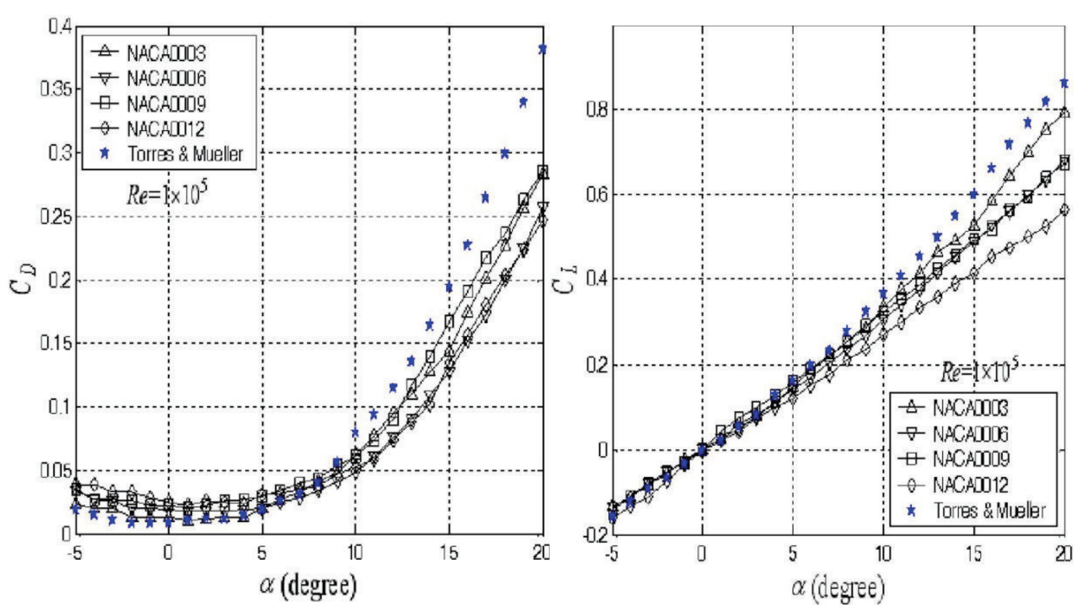

Figure 20. Drag and lift coefficient w.r.t AOA [9]

2.2 Calibrations

Before starting any experiment, calibrations are an important part of the experiment to achieve an accurate result. The focus of this project is to improve the accuracy of Taylor's wind tunnel. Therefore, it is important to know about the losses in each section in the wind tunnel.

Table 14: Taylor's Wind Tunnel Specifications [1]

Taylor's Wind Tunnel Specifications	
Type	Open-circuit or Eiffel
Test Section Cross-sectional area	0.303 m by 0.303 m
Geometrical shape of the test section	Rectangular
Length of the test section	0.885 m
Contraction ratio	3:4:1
Fan Speed	3.33 m/s – 38.85 m/s
Fan diameter	0.63 m
Output torque of a motor	415 V/50 Hz
Motor Horsepower	3 HP

2.3 Velocity distribution along the centerline in Test Section

The purpose behind this study is to ensure the consistency of the velocity along the centerline. Hot wire anemometer was used and positioned at three positions along the centerline in the test section which is shown in Figure 3 and Figure 4. Wind tunnel velocity was initially set at frequency input of 5 Hz which is 3.23 m/s. in order to record the velocity, hotwire anemometer was connected to the datalogger (DO2003) [11]. After the results has been recorded, the experiment was repeated at five operational frequency input of 10, 15, 20, and 25 Hz. The results were then tabulated.

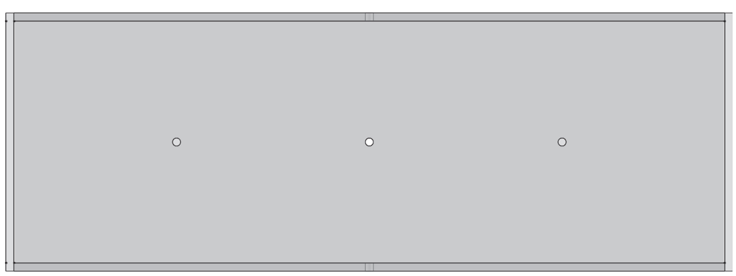

Figure 21. Test Section with 3 centerline holes

Figure 22. Taylor's University Wind tunnel

2.4 Effect of air leakage at 3 different position

The purpose of this experiment is to determine the error contributed on through the air leakage in the test section with or without model. Two condition are created for the purpose of this experiment. The first condition is to create some holes on the walls of the test section. There are total 7 holes on each walls of the test section. One on the top-center, bottom-center, back-center and 4 holes on the front where 3 holes are scattered on the center line and another one is placed above the hole in the center. The test section with holes is illustrated in Figure 11 at Appendix 1. A hot wire anemometer is used to obtained the velocity reading for 3 different position of the front acrylic on 3 different center line positions.

2.5 Effect of the flowrate

On the third experiment in this methodology was conducted in order to identify the how much the experimental flowrate differs from the theoretical values. The experiment was run using different frequency ranges from 5 Hz to 40 Hz with the interval of 2.5 Hz. The flowrate at different frequency is then recorded for 30 second interval for each frequency.

2.6 Effect of the test rig/support system of the model

The experiment is designed for the purpose of measuring the drag and lift on the test rig and to determine how different model affect the support. The outcome of the experiment is that the drag and lift data of the model only should be able to be calculated. The model that were used in this experiment are NACA 0012 finite wing with an aspect ratio of one with test rig and test rig only which are shown Figure 9 and 10 respectively along with the dimensions. The experiment set-up is illustrated in Figure A.2 in Appendix A. Equation (3) will be adopted which was studied by S. Lai [6] as the following:

$$C_{D(model)} = C_{D(total)}\frac{S_{total}}{S_{ref}} - C_{D(Rod)}\frac{S_{Rig}}{S_{ref}} \quad (3)$$

where,
$C_{D(Model)}$ is the drag coefficient of the model.
$C_{D(total)}$ is the total coefficient of drag.
S_{total} , is the total frontal area of the model and test rig.
S_{ref} is the frontal area of the model without the test rig.
$C_{D(rig)}$ is the drag coefficient of the test rig.
S_{rig} frontal area of the test rig.

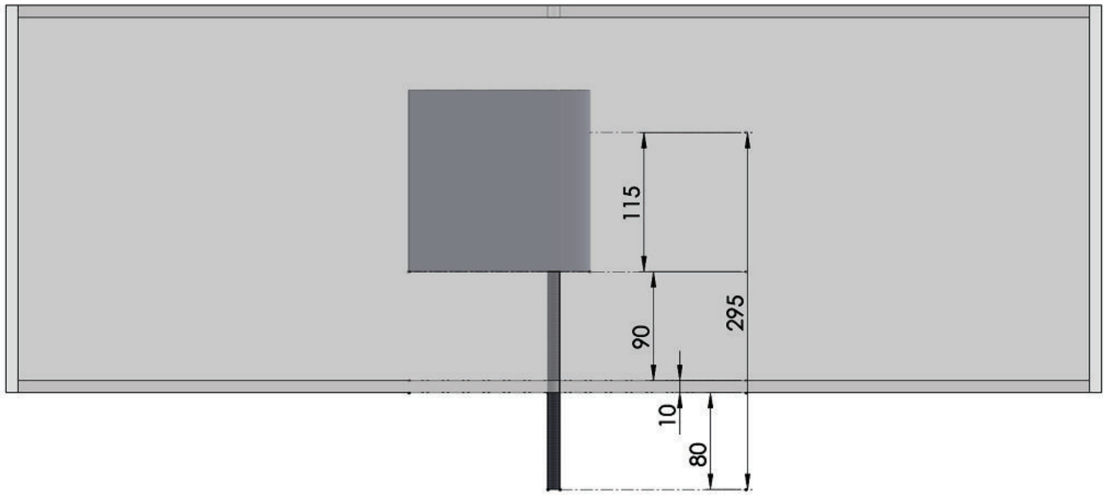

Figure 23. Test Section setup of model with test rig

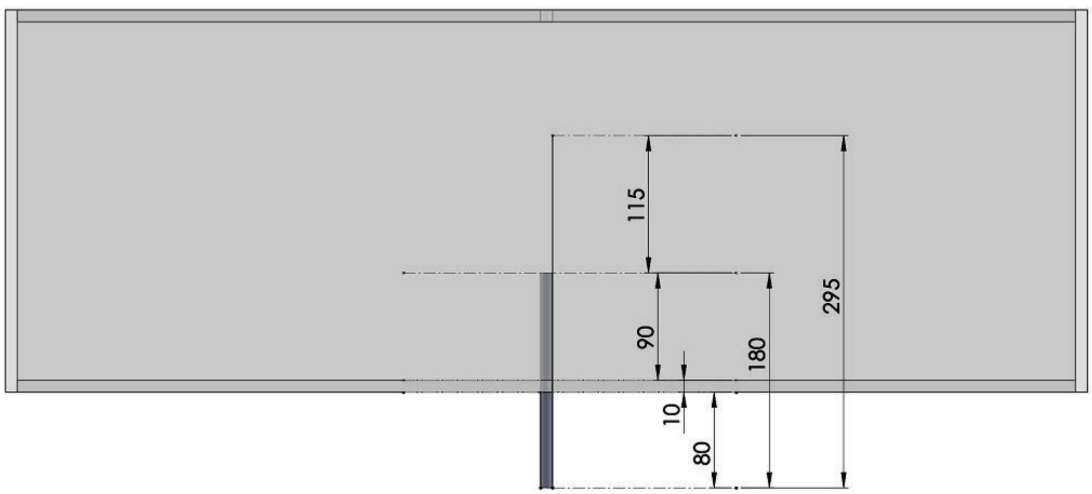

Figure 24. Test section setup only Test rig

2.5 Effect of size of the models

In this last experiment that was conducted was to study on how the effect of size of the model affect the drag and lift measurement in Taylor's University wind tunnel. The models that were used for this experiment are three aspect ratios of NACA 0012 profile which are 0.5, 1.0 and 1.5 and the experiment is run at five angle of attack. Both the drag and lift results on each aspect ratio were recorded and compared with the published paper [9]. From the Figure 7 shown three different aspect ratios of the finite wings of NACA 0012. The chord length for all three airfoils are the same only the span of the airfoil that were modified. In the figure 8, 9, 10 shows the experiment set up of each airfoil according to the aspect ratio. Detailed drawing of each airfoil aspect ratios can be referred at appendix.

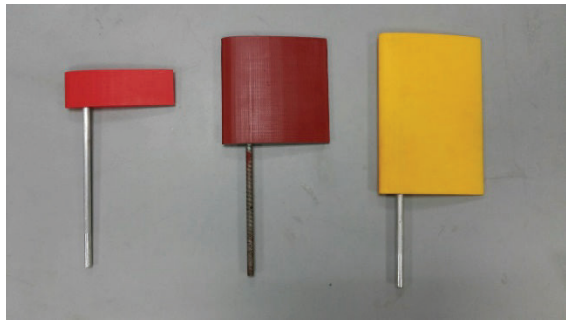

Figure 25. Different aspect ratio of NACA 0012

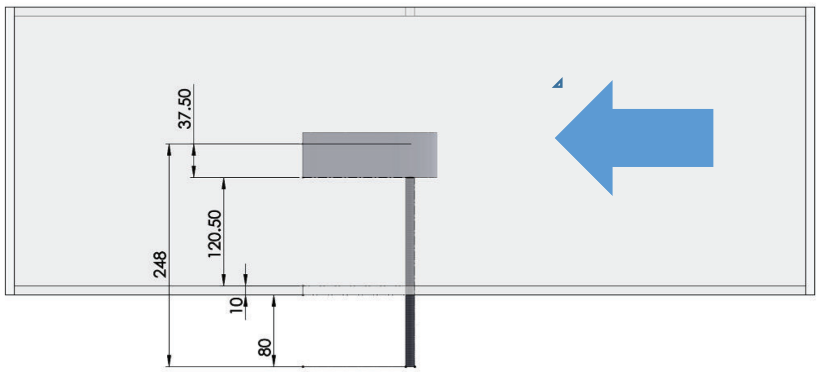

Figure 26. NACA 0012 with AR 0.5 in the Test section

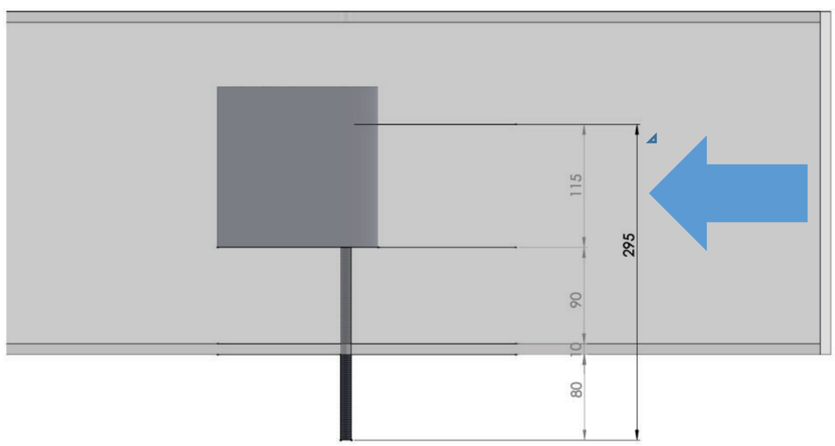

Figure 27. NACA 0012 with AR of 1.0 in the Test section

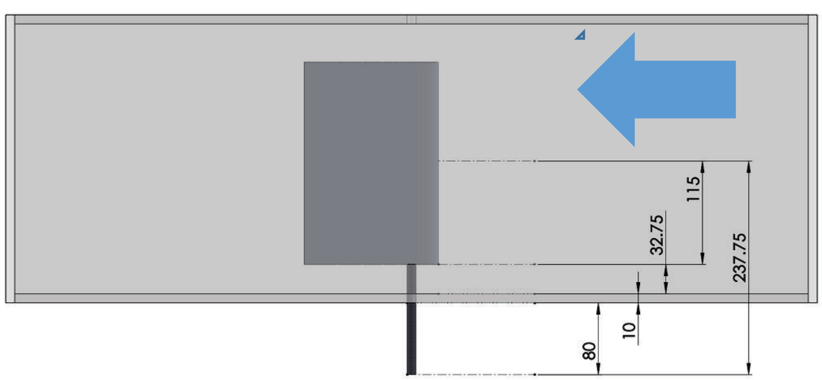

Figure 28. NACA 0012 with AR of 1.5 in the Test Section

3.0 Results and Discussion

This section discusses the experimental results obtained throughout this research. The effects of air leak to the velocity under three different positions, the effects of the test rig to the drag and lift of NACA 0012 with aspect ratio of 1, the effects of size of NACA 0012 on the drag and lift measurement and the effect of flowrate in the test section. The experimental results obtained are validated from the published paper.

3.1 Effect of air leak on the velocity along the center line in the test section under three positions

From the data shown in the Table 2, there are two conditions under the effect of air leak which are with holes and sealed. It can be observed that there is an increase of velocity as the frequency increases. Similar trend can be observed from the three positions where for each the velocity at the same frequency among the positions has not much of a difference.

Table 2. Air leak under 3 different position

	Distance (cm)	Position	5 Hz	10 Hz	15 Hz	20 Hz	25 Hz
with holes	-12	Left	3.39	6.8	10.63	14.25	17.72
	0	Center	3.3	6.63	10.58	13.97	17.12
	12	Right	3.31	6.69	10.28	13.71	16.84
sealed	-12	Left	3.48	6.79	10.62	14.02	17.22
	0	Center	3.38	6.66	10.32	13.76	17.06
	12	Right	3.34	6.74	10.43	13.76	16.77

Moreover, from the Table 3, shows the percentage error distribution between the sealed and leaks conditions in three positions along the centerline of the test section. Table 3 also shows the maximum error percentage is at 2.90% where the minimum goes down to 0.09%.

Table 15. Percentage error distribution of air leak in different positions

	% diff b/n sealed and holes		
Frequency	Left	Center	Right
5	2.59	0.90	2.37
10	0.15	0.74	0.45
15	0.09	1.44	2.52
20	1.64	0.36	1.55
25	2.90	0.42	0.33

In Table 4 shows the summarization of the whole results tabulated from Table 2 and 3, by taking the average of each position of the error percentage contribution and adding each average for three positions to find the average of the average to obtain the final percentage contribution on the overall error contribution of the effect of air leak on the wind tunnel velocity measurement.

Table 16. Average error of air leak in different positions

	Left	Center	Right
Average error	1.47	0.77	1.44
Average of average errors	1.23		
Range error	0.09 - 2.9	0.36 - 1.44	0.33 - 2.52

From the graph shown on Figure 23, there are three positions that are shown in the graph. It can be observed that the error percentage distribution given by air leakage has a higher contribution in the first three frequency which shows that lower speed is prone to air leakage. As the frequency increases shown in the graph, the error distribution decreases.

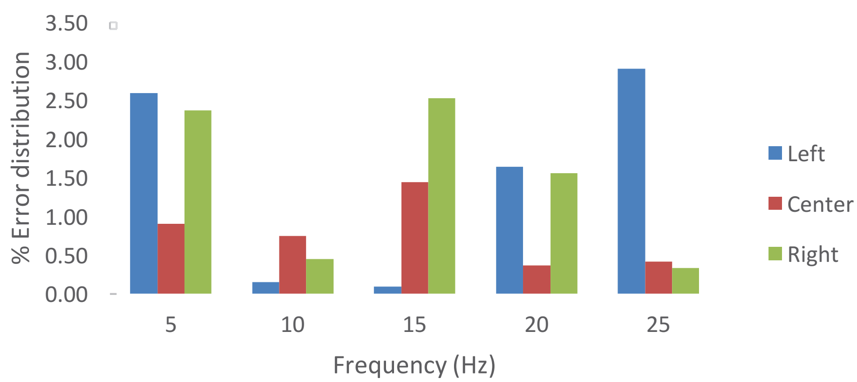

Figure 29. Percentage error distribution of the air leak in.

3.2 Analysis and calculation of the experiment of the effect of flowrate

Table 5 shows the frequency range of 0 to 40 Hz at the interval of 2.5 Hz. In this Table, there are two methods that are used to obtain the flowrate. The first is the theoretical flow rate in which the flowrate is calculated with respect of the desire velocity corresponds to the frequency. The area that is used in the calculation is the cross-sectional area of the test section measured. The second method is the experimental flowrate in which the wind tunnel is run in the range of the desire frequency and the flowrate is measured using the hotwire that is connected to the data logger under 30 second interval for every frequency. It can also be seen from Table 5 that the theoretical flowrate is very close with the experimental flowrate which shows that the flowrate has very little effect on the performance of the wind tunnel. Table 5 also shows that the results of the experimental flowrate have lower values compared theoretical results.

Table 17. Flowrate distribution

Frequency (Hz)	Avg velocity (m/s)	Experimental Flowrate (m^3/s)	Theoretical flowrate (m3/s)	% error difference

5	3.38	1089.70	1095.12	0.49
7.5	4.80	1566.00	1556.28	0.62
10	6.66	2153.30	2157.84	0.21
12.5	8.48	2770.00	2748.60	0.78
15	10.32	3340.00	3343.68	0.11
17.5	12.07	3906.70	3911.76	0.13
20	13.76	4453.30	4457.16	0.09
22.5	15.42	4976.70	4997.16	0.41
25	17.06	5526.70	5528.52	0.03
27.5	18.68	6063.30	6052.32	0.18
30	20.37	6586.70	6598.80	0.18
32.5	22.10	7153.30	7160.40	0.10
35	24.40	7776.70	7905.60	1.63
37.5	25.90	8370.00	8391.60	0.26
40	26.60	9010.00	8618.40	4.54

Table 6 shows the percentage error distribution between the theoretical and experimental values obtained. The error percentage distribution between two methods have mostly lower than one percent of difference except for two values that are highlighted in yellow. The minimum and maximum range of error percentage contribution is from 0.09 to 4.54 percent respectively. The average of average error is 0.65 percent.

Table 18. Error percentage distribution of Flowrate distribution

Range of errors	Average % error difference
0.03 - 4.54	0.65

In Figure 11, the percentage of error contribution can be seen more clearly showing that for most flowrate is lower than one percent. Due to the low percentage contribution, the effect of flowrate can be neglected. However, for better accuracy in using the Taylor's wind tunnel, it is best to include the average of average error percentage for flowrate measurement purpose.

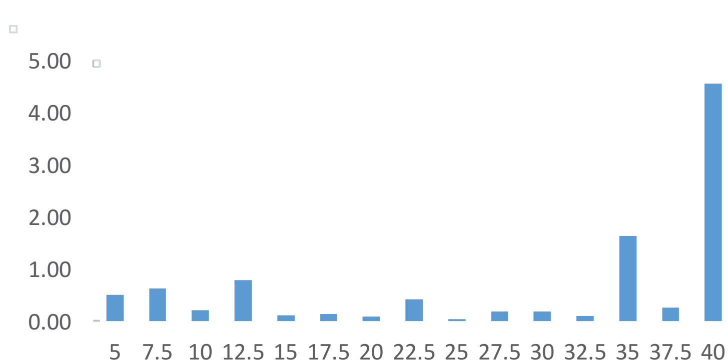

Figure 30. Percentage error distribution of flowrate under different frequency

The theoretical flowrate calculation is calculated as the following:

$$\dot{V} = A \cdot \mathrm{v} \tag{4}$$

$$\dot{V} = (0.0303 \times 0.303)\mathrm{m}^2 \cdot 3.38\ \mathrm{m/s} \cdot \frac{3600\ \mathrm{s}}{1\ \mathrm{h}}$$

$$\dot{V} = 1095.12\ \mathrm{m}^3/\mathrm{h}$$

3.3 Effect of test rig/support system on drag and lift measurement

Table 6, summarizes the result of measurement of drag and lift of the model with the support. Whereas Table 7 shows results of the measurement of drag and lift of the model without the support. Table 8 shows the summary of the error difference obtained from table 6 and 7. The range of the error found in the effect of the test rig on the lift and drag measurement were found to be 1.43% - 32.13%, 11.85% - 41.24% respectively. The support interference on the drag coefficient is found to be more profound than coefficient of lift shown in Figure

Table 19. Effect of model support on the drag and lift measurement with rig

w/h rig	Published paper [9]		Experimental Data		% Error difference	
AR 1	CL	CD	CL	CD	CL	CD
0	0.000	0.025	0.050	0.041	4.984	64.770
5	0.122	0.031	0.161	0.049	32.129	59.925
10	0.271	0.051	0.268	0.068	1.433	33.312
15	0.413	0.136	0.355	0.102	13.963	25.211
20	0.561	0.251	0.469	0.214	16.342	14.706

Table 20. Effect of test rig on the drag and lift measurement without rig

w/o rig	Published paper [9]		Experimental Data		% Error difference	
AR 1	CL	CD	CL	CD	CL	CD
0	0.000	0.025	0.040	0.017	3.97	30.98
5	0.122	0.031	0.165	0.025	35.09	18.19
10	0.271	0.051	0.275	0.045	1.46	11.85
15	0.413	0.136	0.367	0.080	11.21	41.24
20	0.561	0.251	0.485	0.196	13.50	21.63

Table 4 shows the summary of the error percentage found in the effect of test rig experiment. It can be observed that the average errors of condition with rig has a higher lift and drag coefficient error percentage difference compare with condition of without rig at Reynold's number of 1.0 x 10^5; hence model without rig will be closer to the true value compare the model with rig. The method to determine the coefficient of drag and lift with and without rig can be refer using Equations (3) shown in section 3.5 from the study conducted S. Lai [6].

Table 21. Range of errors and average errors of effect of test rig

Conditions	Range of errors		Average errors	
AR 1	CL	CD	CL	CD
w/h rig	1.43 - 32.13	14.71 - 64.77	13.77	39.58
w/o rig	1.46 - 35.09	11.85 - 41.24	13.05	24.78

Moreover, from Figure 11, it is shown that the difference between the percentage error distribution under two conditions such as condition with rig and without rig. For the first two angles, the percentage errors on the model with rig is higher compared to the percentage errors on the model without rig. As the angle increases, it can be seen that the percentage error starts to shift sides especially at the last two angles which are at the angle of 15 and 20 which shows the percentage error of the model without the without rig has a higher error compare to the model with rig.

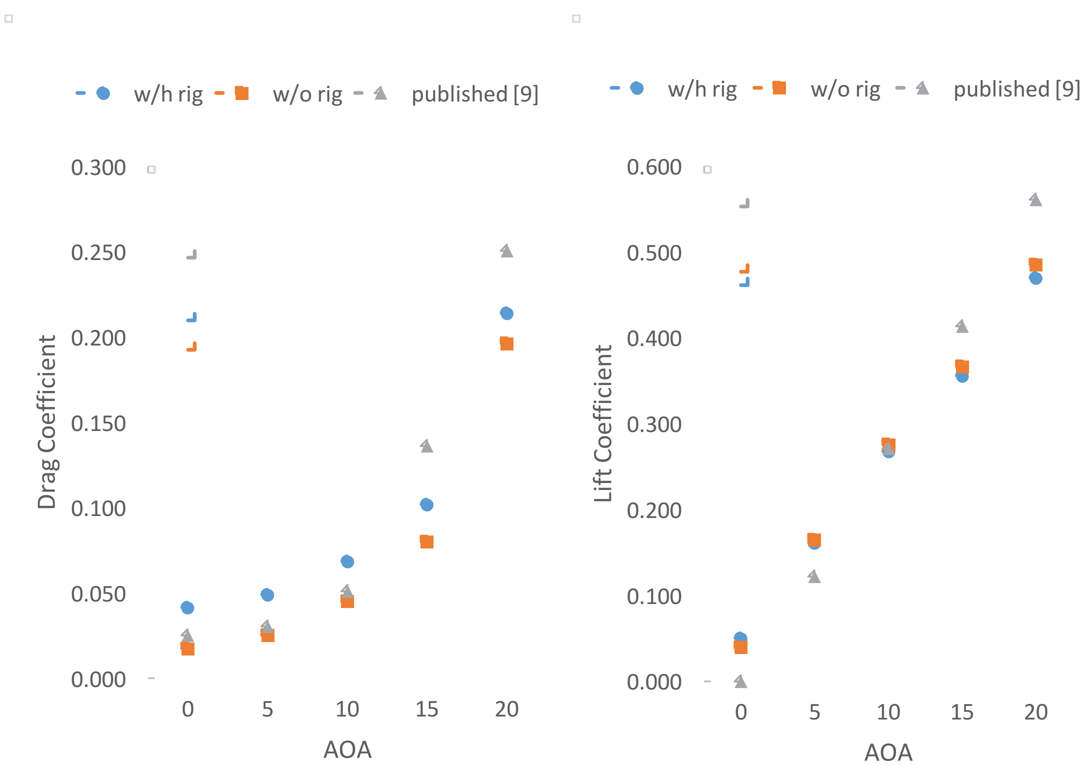

Figure 312. Comparison of drag and lift distribution between with rig, without rig and published paper [9].

3.4 Effect of size of the models on the drag and lift measurement

The purpose of the study of the effect of size initially conceived in order to investigate the effect of the difference of aspect ratio of the same model. Study shows that for streamlined shapes that higher aspect ratio has will have a higher stall angle. Three model were used to investigate on the effect of size on the airfoil with three aspect ratios of 0.5, 1.0 and 1.5. Table 26 shows the percentage error difference of the effect of size of three aspect ratios. It can be observed that the error percentage differences increase with the aspect ratios on the drag and lift coefficient at various angle of attack shown in Table 9.

Table 22. Percentage error differences of different aspect ratio

	% error differences					
AOA	AR 0.5		AR 1		AR 1.5	
	C_D	C_L	C_D	C_L	C_D	C_L
0	28.49	1.76	30.53	0.02	42.30	0.02
5	24.51	57.68	10.27	48.02	58.93	27.85
10	27.27	26.97	42.03	46.47	64.97	2.43
15	37.46	18.81	44.44	38.04	63.12	11.07
20	38.40	6.75	24.54	22.18	31.47	26.80

Figure 13 - 15 shows the drag and lift distribution under the aspect ratio of 0.5, 1.0, and 1.5 the drag distribution deviated more profound as the angle of attack increase.

- At zero AOA, percentage error differences of drag coefficient of AR 0.5 amount to 28.49% with AR 1 of 30.53% and AR 1.5 at 42,30%.
- At AOA of five, percentage error differences of drag coefficient of AR 0.5 amount to 24.51% with AR 1 of 10.27% and AR 1.5 at 58.93%.
- At AOA of ten, percentage error differences of drag coefficient of AR 0.5 amount to 27.27% with AR 1 of 42.03% and AR 1.5 at 64.97%.
- At AOA of 15, percentage error differences of drag coefficient of AR 0.5 amount to 37.46% with AR 1 of 44.44% and AR 1.5 at 63.12%.
- At AOA of 20, percentage error differences of drag coefficient of AR 0.5 amount to 38.40% with AR 1 of 24.54% and AR 1.5 at 31.47%.

Figure 13 - 15 also shows that both lift and drag coefficient under three aspect ratios have a gradual increase of deviation as the aspect ratio increases with an increase of AOA. Higher aspect ratio leads to a higher error contributions. Therefore, future user who will be using the TUWT at higher aspect ratio will have to expect that high error percentage will occur especially when measuring drag coefficient.

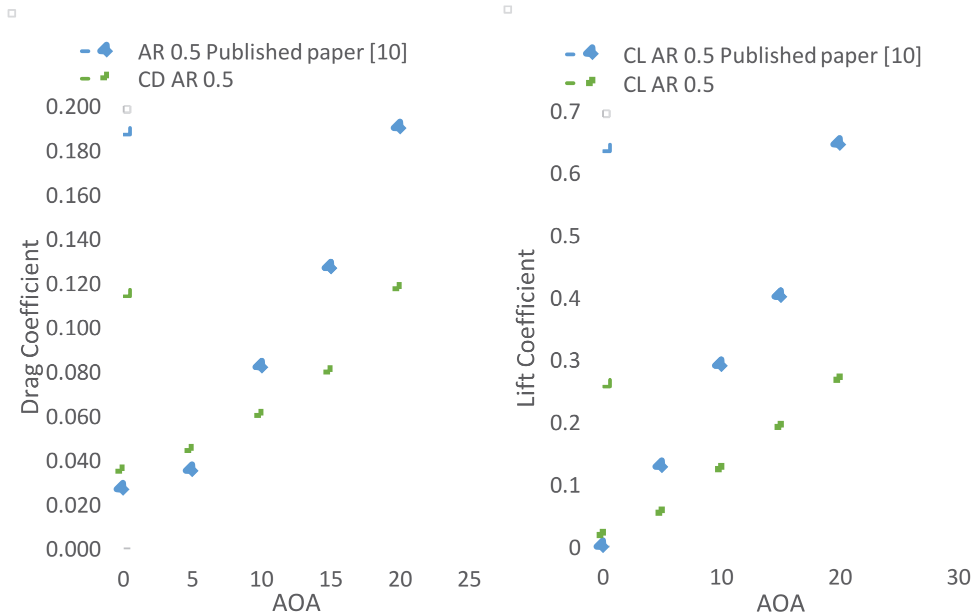

Figure 13. Drag and Lift distribution under aspect ratio of 0.5 at various angle at Re no of 1.23×10^5

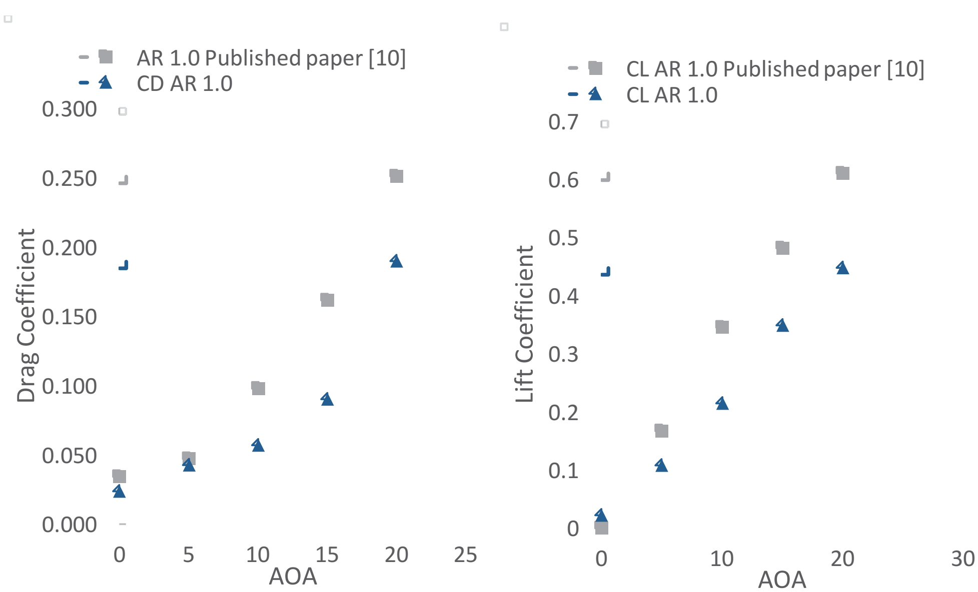

Figure 32. Lift distribution under aspect ratio of 1.0 at Re no of 1.0×10^5 at Re no of 1.23×10^5

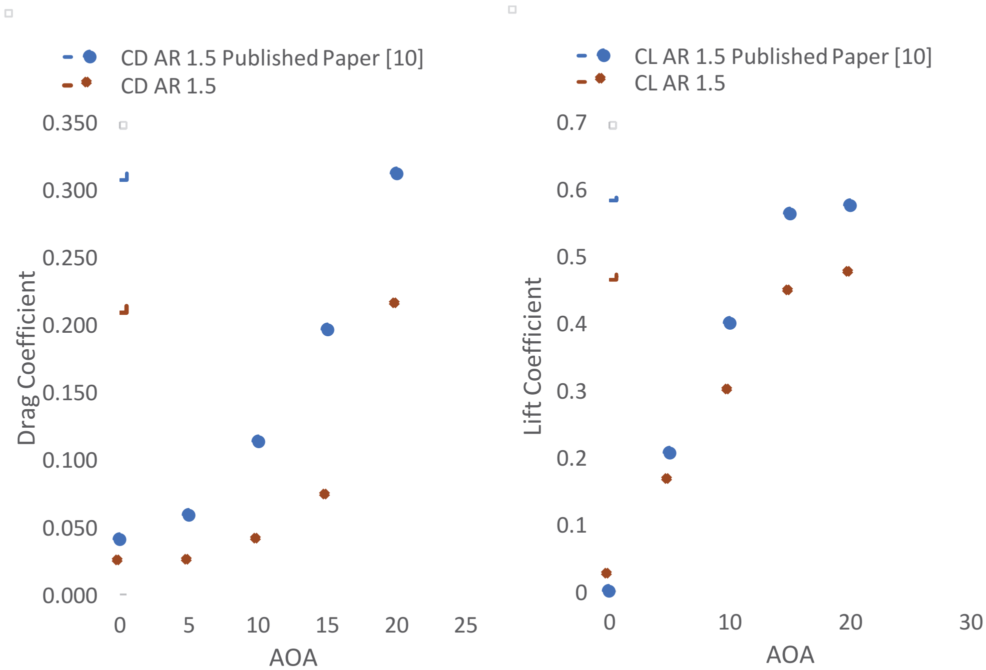

Figure 33. Lift distribution under aspect ratio of 1.5 at Re no of 1.23 x 10^5

3.5 Summary of sources of errors

From the Table 10, shows the sources of error percentage of error from minimum to maximum of the 4 effects studied in the wind tunnel. This table helps to provide insight for the students or experimenter to take into consideration of the errors that they may encounter throughout the wind tunnel test.

Table 23. Sources of errors summarized

Experiment no:	**Sources of error**	**Parameters**	**Range of errors**				**Average errors**		**Average of average errors**	
1	**Airleak**	Velocity	Min		Max					
Positions		Left (-24 cm)	0.09		2.90		1.47		1.23	
		Center (0)	0.36		1.44		0.77			
		Right (24 cm)	0.33		2.52		1.44			
2	**Flowrate**	Flowrate	0.10		4.50		0.65		0.65	
3	**Test rig**	Lift and Drag	CD	CL	CD	CL	CD	CL	CD	CL
Conditions		With Rig	14.71	1.43	64.77	32.13	39.58	13.77	32.18	13.41

		Without Rig	11.86	1.46	41.24	35.09	24.78	13.05		
4	**Model size**	Lift and Drag	CD	CL	CD	CL	CD	CL	CD	CL
Aspect Ratio		AR 0.5	24.51	1.83	38.40	57.68	31.64	24.69		
		AR 1.0	28.69	0.47	63.36	44.20	49.94	28.38	46.76	23.04
		AR 1.5	30.66	2.32	69.93	32.55	58.69	16.06		

4.0 Conclusion

In the study of improving the accuracy of Taylor's wind tunnel measurement experimentally. Four types of experiments were conducted. Four different parameters were considered in identifying the error sources in the Taylor's wind tunnel. The effect of these parameters is summarized as follows

- The effect of air leak on the velocity along the center line is very small which almost can be neglected. However, for better accuracy, the experimenter may be able to take into consideration of the errors by estimating the errors at 1.23%.
- The effect of flowrate in the wind tunnel test section at different frequency average of average errors is at 0.65%
- The effect of test rig which are conducted in the wind tunnel contributes major amount of average of average errors of drag and lift measurement of 32.18% and 13.41% respectively which means the drag and lift measurement are 32.18% and 13.41% lesser than the obtained result.
- The effect of model size on the lift and drag measurement in the wind tunnel have average of average errors of drag and lift measurement of 46.76% and 23.04% respectively which means the drag and lift measurement are 46.76% and 23.04% lesser than the obtained result for different aspect ratios.

The percentage error contribution in the wind tunnel can be further identified by conducting other experiments involving the drag and lift such as

- The effect of angle of attack on the drag and lift measurement of NACA 0012 in the wind tunnel
- The effect of shapes on the drag and lift measurement in the wind tunnel
- The effect of lab conditions in the wind tunnel
- The effect of rigidity of the connections of test rig with the load cell

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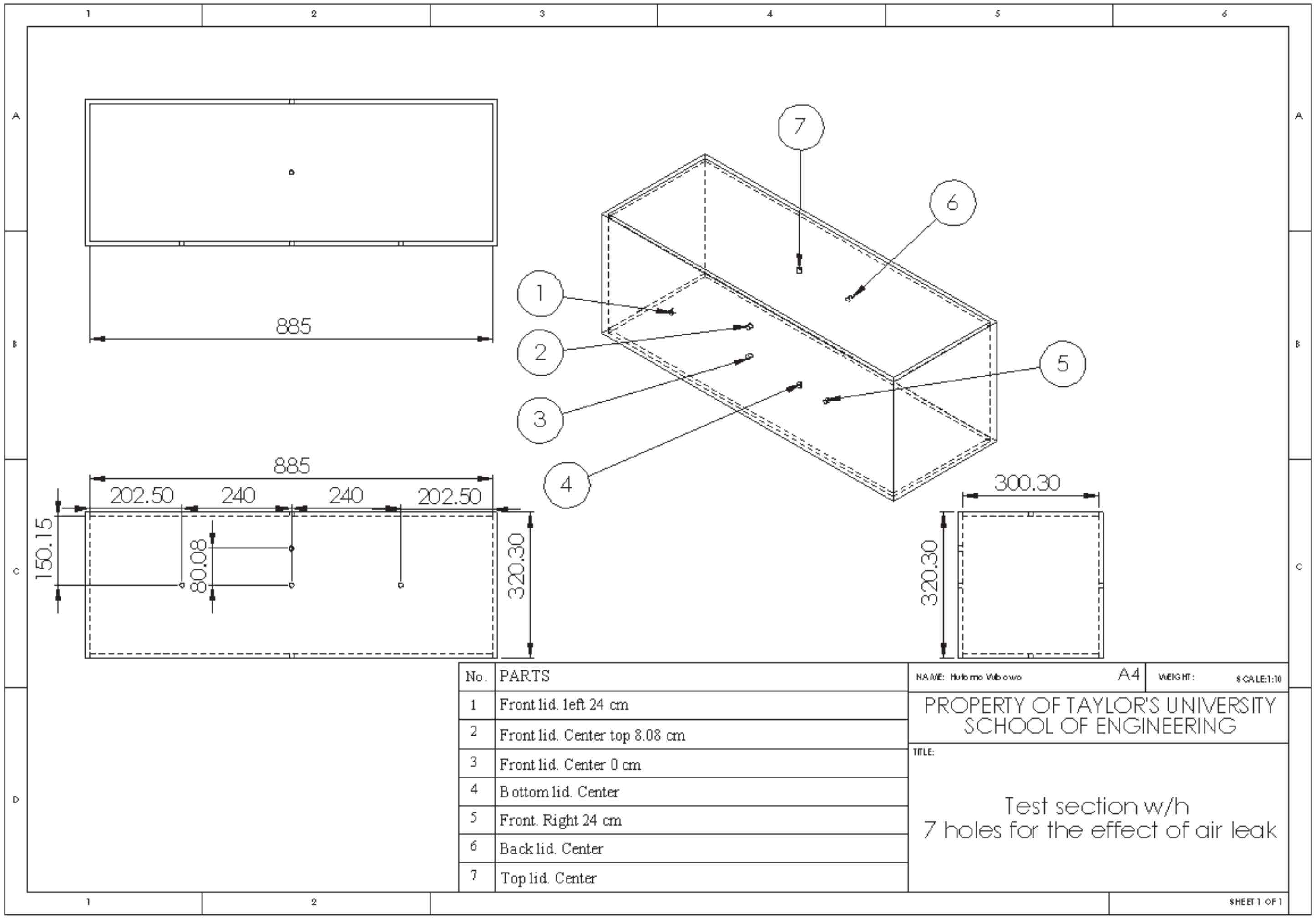

Figure 341. The effect of air leak experimental set-up

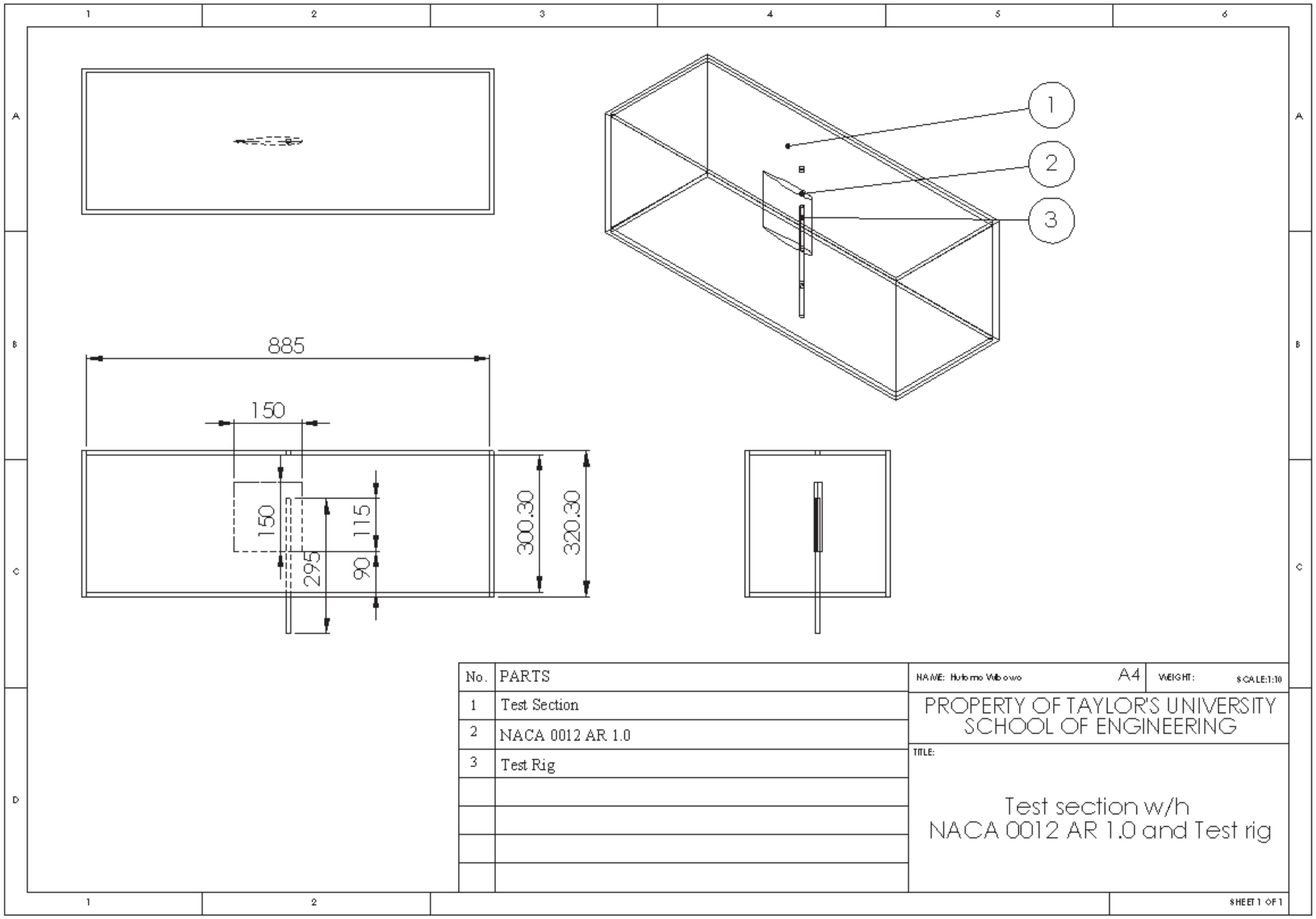

Figure 135. The effect of test rig experimental set-up