TESTING OF A DASH 8 Q400 IN THE NASA AMES 80X120' WIND TUNNEL

J.D.Lye Bombardier Aerospace,
S.Buchholz Sverdrup Technology (under contract to NASA),
D.Nickison NASA Ames

Keywords: *NASA Ames 80x120 wind tunnel Bombardier Dash 8 Q400 crosswind forces moments*

Abstract

In 2000 a need arose to test a full scale Dash 8 Q400 turboprop aircraft in the 80x120 foot wind tunnel, at the NASA Ames National Full-Scale Aerodynamics Complex (NFAC). The main purpose was to simulate aircraft ground operations in very strong winds, and record propeller blade strains in these conditions, for certification purposes.

This task involved lifting a complete airworthy flight test aircraft into the wind tunnel, where the Main Landing Gear (MLG) was secured onto steel pads at the wind tunnel floor level.

Loads applied to the MLG were carefully considered. The total aerodynamic sideload in a 90-degree crosswind of 65 knots was estimated to be over 17,000 lbf. Aircraft yawing moments were restrained by differential X loads (fore & aft) on the MLG. The effects of engine and propeller thrust were also considered.

Force & moment data from the balance were monitored during the testing, and were compared to the pre-test estimates.

An onboard crew of two Test Pilots and one Flight Test Engineer, from the Bombardier Flight Test Center (BFTC) in Wichita, operated the aircraft in the tunnel, with either the left or the right engine running.

Wind-on testing was done on three consecutive night shifts, with no significant problems. A total of 124 data points were taken, at three yaw angles (beta) of 142, 225 and 270 degrees, in windspeeds up to 65 kts (75 mph or 120 km/hr).

After the testing, the aircraft was quickly returned to airworthy condition, and flew back to BFTC on the day after the lift-out from the wind tunnel. The test was successful in obtaining precise propeller blade strain data, in accurately controlled strong wind conditions, and in the presence of completely realistic airframe influences.

Although the 80x120' tunnel was designed to accommodate full scale aircraft, the Q400 with a span of over 93 feet and length of over 107 feet, was certainly the largest aircraft yet tested in this facility, or in any other wind tunnel.

The main purpose of this paper is to present some information on forces and moments experienced by the Q400 in a 90-degree crosswind, including the effects of various power settings on the downwind propeller.

1 Introduction

The Q400 is the largest and most powerful passenger turboprop in production [1]. It is fitted with PW150A engines rated at 5,071 shp, and 6-bladed Dowty R408 propellers. This aircraft is sometimes required to operate on the ground in very strong winds, and in order to accurately assess propeller fatigue life it was necessary to obtain accurate experimental data in very strong winds.

Preliminary feasibility studies began in April 2000, to determine if it would be possible to test the Q400 in the NASA 80x120' wind tunnel [2].

Questions included :-
Would it fit on the crane, and in the tunnel?
Would it be safe to test with a crew on board?
How would we acquire data?
These (and many more) questions were all resolved successfully, and the decision to go ahead was given on 19 July 2000, with a test window starting in early September.
The aircraft (#4001) flew into Moffett Field on 5 September 2000, and was lifted into the tunnel on 8 September, with the first wind-off engine runs conducted on the same day. Wind-on testing was conducted on three consecutive night shifts, from 11-13 September. The aircraft was lifted out on 14 September and flew back to BFTC in Wichita on 15 September 2000.

2 Test Preparations

2.1 NASA Ames facility preparations

The first challenge was in preparing to get the aircraft from the adjacent airfield (Moffett Field) to the wind tunnel facility. Routes used for transporting smaller wind tunnel models were not suitable for the full-scale Q400 turboprop (which is larger in span and length than a Boeing 737-200). The best route required the making of a new gravel causeway, to bridge an area of grassland.
A new lifting rig was designed and constructed at NASA, to support the aircraft on its three standard jacking points, and allow it to be lifted into the tunnel. The NASA crane had plenty of weight capacity (well over twice the requirement).

In terms of size, the gap between the crane frame stanchions (about 88 feet) was less than the aircraft wing span and the aircraft length. This meant that the lift-in plan involved placing the aircraft axis at 45 degrees to the crane axis, and using 'tag lines' to control swinging and rotation of the aircraft on the crane hook.
To support the MLG on the floor of the tunnel, two new steel floor pads were made, connected to the underfloor balance frame via short struts. Steel buttresses were designed and built to restrain the MLG in the X direction, wooden blocks were prepared to fit between each pair of MLG tires to restrain Y forces, and heavy duty fabric straps were prepared, to clamp down all four MLG tires securely.

2.2 Aircraft preparations

All fuel was drained from the aircraft fuel tanks, for safety, and the aircraft was modified so that it used an external fuel supply. It was also necessary to arrange for nitrogen purging of the fuel tanks while running the engines.

Both of these modifications were accomplished in a relatively simple and easily reversible manner. Each engine had two flexible fuel hoses, near the top of the nacelle, connecting the engine to the airframe fuel system. The larger hose (3/4" ID) served as the fuel supply and was disconnected from the engine, to be replaced by a new hose to supply fuel from the external NASA supply. The smaller hose (1/2" ID) connecting the engine to the airframe was for returning pressurized fuel from the engine to the wing tank, to power jet pumps. This hose was disconnected and capped to prevent fuel from leaving the engine. A new hose was added to supply nitrogen (instead of fuel) to the wing tanks. The existing fuel tank vents served to vent the nitrogen from the tanks.

A hatch in the upper surface of each nacelle was replaced with a temporary replacement panel, which had 2 holes in it, to allow fuel and nitrogen hoses to enter into the nacelle.

The right propeller was fitted with strain gauges on two of the six blades, by the propeller manufacturer, Dowty Aerospace Propellers. This strain gauge system had been used before at BFTC for flight tests of the Q400, and for ground operations in high winds.

Three electrical cables were routed between the Q400 fuselage and the wind tunnel control room. These were for the Dowty strain gauge data system, the wind tunnel intercom system, and the wind tunnel emergency stop system. In previous BFTC testing with this Dowty data acquisition system, a Dowty engineer had been monitoring the data from a position inside the aircraft cabin, but for this wind tunnel test program it was more convenient and safer to route the signals to the wind tunnel control room, where the data were recorded and monitored.

2.3 Preparations for aircraft crew safety

Testing with engines running is a routine operation in the 80x120' wind tunnel, but testing with an on-board crew is not standard operating procedure. Extensive assessment and analysis work was done, to ensure that proper plans were in place to cover all conceivable contingencies, including safe evacuation of the crew from the aircraft and the test section, in the event of an emergency. The fire crew from Moffett Field was in attendance for all engine-running periods. A crew of three was on board the aircraft, consisting of two BFTC flight test pilots, and one BFTC flight test engineer.

3 Outline of Testing Procedures

3.1 Data Acquisition Systems

The aircraft (#4001) was the first Q400 to fly, in January 1998, and was fitted with an extensive flight test data acquisition system, known as ITAS. This system was used in the same manner as on previous flight tests and ground tests. Telemetry was an option, but it was decided that this was not necessary, so all data were recorded using on-board equipment. The concept was essentially to conduct 'routine' BFTC engine ground runs, in the wind tunnel test section. Two other separate data systems were also employed; the Dowty strain gauge system and the NASA wind tunnel system. All three systems were kept separate, and were simply synchronized in terms of time. The NASA system was only used to record very basic wind tunnel data, such as turntable angle, balance data, and airspeed.

3.2 Yaw Angles

The three yaw angles tested were essentially two quartering tailwinds and a 90-degree crosswind from the left, and were based upon Dowty experience of the appropriate conditions to test. The right quartering tailwind (beta 135) happened to fall within a 16-degree arc of the turntable that was inaccessible, so the closest available angle (142 degrees) was used instead. The sequence was 142, 225, then 270 degrees.

Some testing was done to check nacelle internal temperatures in a strong quartering tailwind. Because of the particular design of the nacelle ventilation and cooling system, the appropriate beta was 225 degrees, with the left engine operating, and the right engine shut down.

As might be expected, there was initially some confusion between the two established sign conventions for yaw. The traditional wind tunnel yaw angle, signified by the Greek letter psi, is equal in magnitude but opposite in direction to the traditional aeronautical engineering yaw angle, signified by the Greek letter beta. Beta is used in this paper.

3.3 Start-up & Data Acquisition Process

The typical test process at each yaw angle was begun by using a ground power cart in the test section (rather than the aircraft batteries) to start the right engine. Then the ground crew, with cart, withdrew from the test section, and all test section doors were closed. Then the wind tunnel fans were started, and the airspeed was brought up to 20 knots. The on-board crew reported (on the wind tunnel intercom) when the aircraft engine and propeller were both adjusted to be 'on-condition'. All the key people were using headsets, and the intercom was also connected to a loudspeaker in the control room. When 'on-condition', all three data acquisition systems were triggered, to take a coordinated data point. After all three data systems had finished taking data, the crew set the next, higher, engine power setting, and then reported 'on-condition'. As an example of productivity, the 39 data points, at eight wind speeds, which were taken at 270 degrees beta, were obtained in 53 minutes. This is a respectable data acquisition rate when compared to flight testing.

3.4 Engine and Propeller Settings

The Q400 employs modern electronic systems for control of the engines and propellers, including Full Authority Digital Engine Control (FADEC) units and Propeller Electronic Controller (PEC) units.

The two cockpit control levers for each engine are traditional in appearance, but modern in function. The Power Lever is similar in concept to the traditional engine throttle lever, but it also has some control over propeller pitch, such as the selection of Reverse Thrust. Power Lever Angle (PLA) is used to represent the engine power setting.

The Condition Lever is similar in concept to the traditional propeller rpm lever.

The intention of this test program was to use typical Power Lever and Condition Lever settings, appropriate to ground operations in service, such as taxiing up a moderate gradient, and performing the propeller Overspeed Governor (OSG) test, which must be done in service periodically. The Condition Lever was set at 'Max/1020' for all test points, but actual rpm was lower than 1020, because of the relatively low power, and (during the OSG test) the OSG control system.

The minimum PLA tested was at the Disc setting, which represents a nominal zero thrust case with propeller pitch approximately zero. The next PLA setting was Flight Idle, and this position, like Disc, was easily set because of a detent in the Power Lever quadrant. The next two PLA settings, nominally 500 shp and 750 shp, were set using the on-board instrumentation systems.

The final power condition was set by selecting a cockpit OSG TEST switch to TEST, and then advancing PLA up to 1500 shp, with the propeller automatically governing to a nominal 860 rpm.

4 Presentation of illustrations and data

Table 1 presents a summary of the data points obtained at a yaw angle (beta) of 270 degrees, and also provides the sign convention for MLG forces in aircraft body axes.

Only data at this particular yaw angle are presented, because in this case the engine and propeller were at exactly 90 degrees to the airflow, giving the clearest distinction between propulsive effects and windspeed effects on the MLG forces and moments. The Yawing Moment as measured by the balance is also shown on Table 1. The Moment Reference Center (MRC) for data processing was positioned on the wind tunnel floor, on the aircraft centerline, midway between the two MLG positions.

As noted on the Table, only the right engine was operating when these data points were acquired, and the left prop was securely tethered.

Figures 1, 2 & 3 are photographs taken during this test period, and give some idea of the logistics involved in getting this test done.

Figures 4 & 5 show both predicted and actual MLG force data, for X & Y directions. Figure 6 shows predicted and actual Yawing Moments.

5 Discussion of MLG force & moment data

5.1 Pre-Test Estimation of MLG Loads

In order to estimate the X, Y & Z loads at both left and right MLG struts, a search was started, looking for wind tunnel data for a similar airframe in a 90-degree crosswind. No relevant data were found, so estimates were generated using Hoerner [3]. A side-view drawing of the Q400 was broken down into five segments; a nosecone, a cylindrical barrel, a tailcone, a flat-plate fin, and a flat-plate dorsal fin.

For estimation of sideforce and yawing moment, drag coefficients of 0.8, 1.2, 0.8, 2.0, 2.0 were applied to these five elements, to produce the trend lines shown on Figures 4-6, (but for future reference a value of 1.8 to replace 2.0 was later found to give a better match with the data).

The nosewheels were assumed to provide no yaw restraint, as they were turned 90 degrees to the fuselage axis, and were free to roll. The Y station of the MLG and propeller (173") was used to add in thrust estimates for the propeller and engine exhaust. It was assumed that thrust would affect the yawing moment and X forces, but not the Y forces. No estimate was made of airframe aerodynamic forces in the X direction.

5.2 Discussion of X Forces on MLG

As the right engine was located at the same Y station as the right hand MLG strut, it was estimated that the left MLG should be insensitive to PLA setting on the right engine. Thus Figure 4 shows two estimated trend lines for the RH MLG, and only one trend line for the LH MLG. A nominal thrust estimate of 6,600 lbf was used for all the 1500 shp / OSG cases.

The actual data generally showed the expected patterns, the engine power affected the RH MLG far more than the LH MLG. The variation of the actual data with windspeed matched the predictions quite well.

5.3 Discussion of Y Forces on MLG

Figure 5 shows a single estimated trend line, applicable to both LH & RH MLG struts, at all power settings.

The actual data points showed a reasonably good correlation in terms of windspeed, and also showed that increasing power increased the magnitude of the sideforce. Increasing power tended to act like increasing windspeed. With more airflow through the propeller as power is increased, lower pressures on the right side of the fuselage would be expected, which would be one way to account for this effect.

5.4 Discussion of Yawing Moments

Figure 6 shows the pre-test estimated trend lines with power off, and on, as compared to the actual data. Positive yawing moment is defined as tending to make the nose of the aircraft swing to the right, so a negative moment indicates positive directional stability.

The 'Disc' data points agreed reasonably well with the power-off trend line.

When the effects of power are considered, it can be seen that increasing power on the right hand engine tended to make the nose yaw to the left, as expected. The 1500 shp trend line uses the same nominal 6,600 lbf thrust value, as shown on Figure 4.

5.5 Analysis of Combined MLG Loads

It is possible, from the data in Table 1, to make a simple analysis of the combined effects of X & Y forces, and Yawing Moment, and the data points taken at 50 knots are used here as an example.

In body axes, over the thrust range tested, X force change was 3,684 lbf, the Y force change was 1,872 lbf, and the yawing moment change was 108,146 lbf.ft.

It is necessary, for this analysis, to make the assumption that there was no significant net X force arising from pressure distributions around the airframe (eg nosecone & tailcone), as a result of the crosswind.

The propulsion effect (adding 3,684 lbf at a lateral arm of 14.42 feet) should have produced a nose left (-ve) yawing moment of 53,123 lbf.ft. If this is subtracted from the total yawing moment, then the remaining moment is 55,023 lbf.ft.

If this remaining moment was solely the result of the sideforce of 1,872 lbf, then this sideforce must be applied at a point about 29 feet aft of the MLG, in the region of the aft baggage door .

The true picture is likely to be somewhat more complex than that described above, but this simple analysis seems to offer a reasonable explanation of the basic effects.

6 Conclusions

1) New NASA equipment, suitable for lifting large airframes into the 80x120' tunnel, and supporting aircraft at the floor of the tunnel, on the balance, was developed and commissioned, as part of this test program. This equipment opens up new test capabilities for research, development and certification testing related to various aerodynamic and propulsion issues.

2) A wind tunnel test was successfully completed in the NASA 80x120' wind tunnel, using a complete airworthy Dash 8 Q400 aircraft, with an elapsed time of ten days from flight in to flight out.

3) As the aircraft main landing gear loads were measured by the wind tunnel balance system, some unique full-scale force and moment data were acquired, for a large turboprop regional aircraft in a 90-degree crosswind, including effects arising from power variations on the downstream engine.

7 References

[1] www.bombardier.com

[2] http://windtunnels.arc.nasa.gov

[3] Hoerner S.F. *Fluid-Dynamic Drag.* 2nd Edition, Published by the Author, 1958.

Table 1 Summary of MLG Forces at Beta 270 degrees

NASA Run 14 Data Point	BETA	Q	Wind Speed	Power Lever Angle	Nominal Prop RPM	Forces applied to LH & RH Main Landing Gear (lbf) LHX	RHX	LHY	RHY	LHZ	RHZ	Yawing Moment (ft.lbf)
#	(deg)	(psf)	(kts)	RH engine only		+ve aft		+ve right		+ve up		See Note
3	270	1.35	20	Disc	660	-474	638	-858	-858	21,840	21,696	-16,143
4	270	1.34	20	Flight Idle	660	-1,199	2,891	-1,132	-1,132	21,568	21,399	-59,391
5	270	1.34	20	500 shp	700	-1,487	3,717	-1,297	-1,297	21,520	21,284	-75,565
6	270	1.34	20	750 shp	780	-1,720	4,430	-1,390	-1,390	21,376	21,137	-89,307
7	270	1.34	20	1500 / OSG	850	-2,218	5,809	-1,715	-1,715	21,366	21,069	-116,553
8	270	3.00	30	Disc	660	-1,030	1,338	-1,903	-1,903	22,011	21,687	-34,378
9	270	2.99	30	Flight Idle	660	-1,822	3,677	-2,300	-2,300	21,753	21,386	-79,847
10	270	2.98	30	500 shp	690	-2,019	4,284	-2,377	-2,377	21,663	21,306	-91,520
11	270	2.98	30	750 shp	790	-2,267	5,067	-2,461	-2,461	21,568	21,209	-106,500
12	270	2.98	30	1500 / OSG	840	-2,892	6,928	-2,762	-2,762	21,196	20,735	-142,588
13	270	5.19	40	Disc	660	-1,739	2,163	-3,289	-3,289	22,368	21,802	-56,669
14	270	5.16	40	Flight Idle	660	-2,537	4,583	-3,637	-3,637	22,047	21,429	-103,390
15	270	5.16	40	500 shp	670	-2,693	5,039	-3,723	-3,723	21,909	21,298	-112,280
16	270	5.15	40	750 shp	760	-3,015	5,962	-3,905	-3,905	21,811	21,211	-130,351
17	270	5.14	40	1500 / OSG	840	-3,584	7,630	-4,198	-4,198	21,569	20,970	-162,837
18	270	6.65	45	Disc	660	-2,197	2,654	-4,220	-4,220	22,613	21,882	-70,444
19	270	6.63	45	Flight Idle	660	-3,040	5,245	-4,565	-4,565	22,324	21,532	-120,298
20	270	6.63	45	500 shp	660	-3,175	5,601	-4,661	-4,661	22,211	21,428	-127,431
21	270	6.63	45	750 shp	750	-3,467	6,433	-4,834	-4,834	22,002	21,209	-143,753
22	270	6.61	45	1500 / OSG	840	-4,067	8,190	-5,150	-5,150	21,786	21,027	-177,985
23	270	8.27	50	Disc	660	-2,746	3,318	-5,271	-5,271	22,901	21,990	-88,046
24	270	8.25	50	Flight Idle	660	-3,622	6,015	-5,618	-5,618	22,581	21,603	-139,938
25	270	8.25	50	500 shp	660	-3,722	6,295	-5,684	-5,684	22,531	21,547	-145,453
26	270	8.27	50	750 shp	750	-4,026	7,115	-5,899	-5,899	22,316	21,337	-161,766
27	270	8.22	50	1500 / OSG	840	-4,628	8,884	-6,207	-6,207	21,906	20,948	-196,192
28	270	9.80	55	Disc	660	-3,260	3,944	-6,251	-6,251	23,155	22,072	-104,608
29	270	9.78	55	Flight Idle	660	-4,149	6,702	-6,592	-6,592	22,789	21,628	-157,567
30	270	9.77	55	500 shp	660	-4,260	7,037	-6,639	-6,639	22,721	21,568	-164,050
31	270	9.75	55	750 shp	740	-4,560	7,867	-6,842	-6,842	22,651	21,487	-180,447
32	270	9.75	55	1500 / OSG	840	-5,142	9,496	-7,202	-7,202	22,225	21,077	-212,548
33	270	11.81	60	Disc	660	-3,930	4,800	-7,495	-7,495	23,501	22,198	-126,763
34	270	11.80	60	Flight Idle	660	-4,865	7,705	-7,848	-7,848	23,103	21,691	-182,518
35	270	11.80	60	500 shp	660	-4,959	7,970	-7,906	-7,906	23,071	21,670	-187,747
36	270	11.78	60	750 shp	720	-5,208	8,687	-8,040	-8,040	22,969	21,567	-201,770
37	270	11.78	60	1500 / OSG	850	-5,835	10,452	-8,430	-8,430	22,588	21,200	-236,505
38	270	13.83	65	Disc	660	-4,639	5,762	-8,760	-8,760	23,830	22,291	-151,031
39	270	13.79	65	Flight Idle	660	-5,567	8,679	-9,087	-9,087	23,413	21,765	-206,857
40	270	13.79	65	500 shp	660	-5,690	8,995	-9,188	-9,188	23,431	21,781	-213,244
41	270	13.79	65	750 shp	730	-5,964	9,828	-9,301	-9,301	23,269	21,618	-229,314

Note : A Positive Yawing Moment is a Clockwise Moment when viewed from above, tending to make the nose yaw right.

Figure 1 Lifting the Aircraft into the 80x120' Wind Tunnel

Figure 2 Showing Fuel & Nitrogen Hoses, MLG Restraints & Turntable

Figure 3 Looking upstream at a Beta angle of 270 degrees

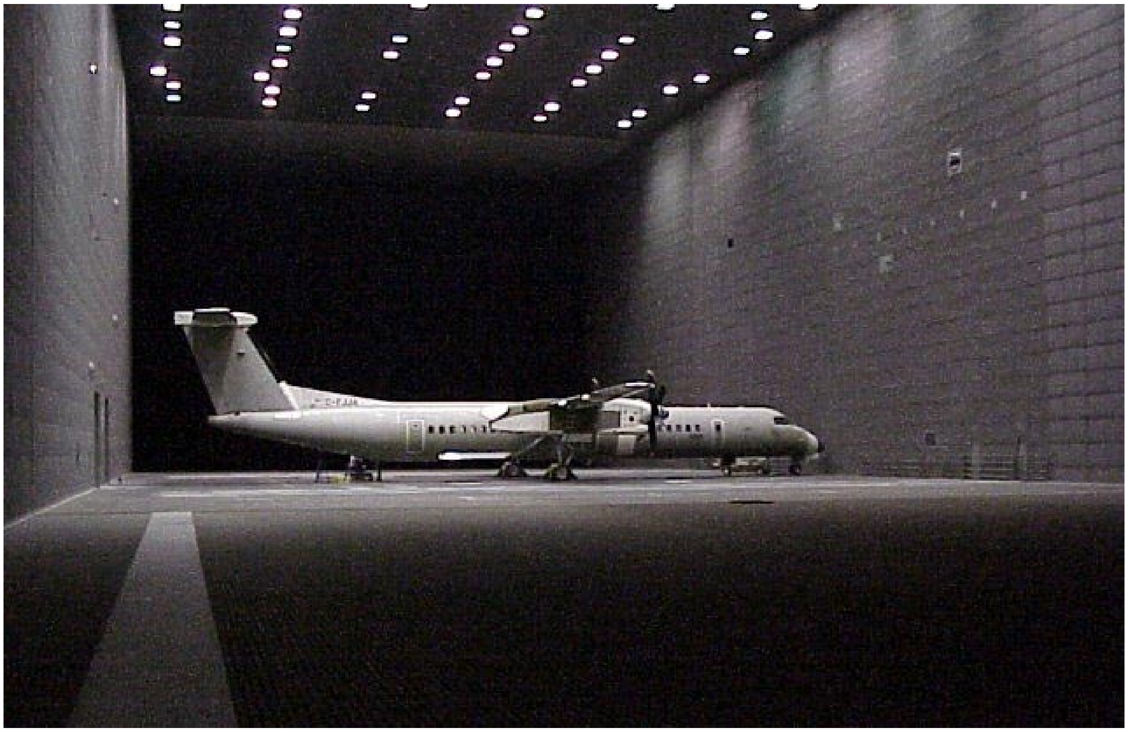

Figure 4 X Loads applied to the MLG

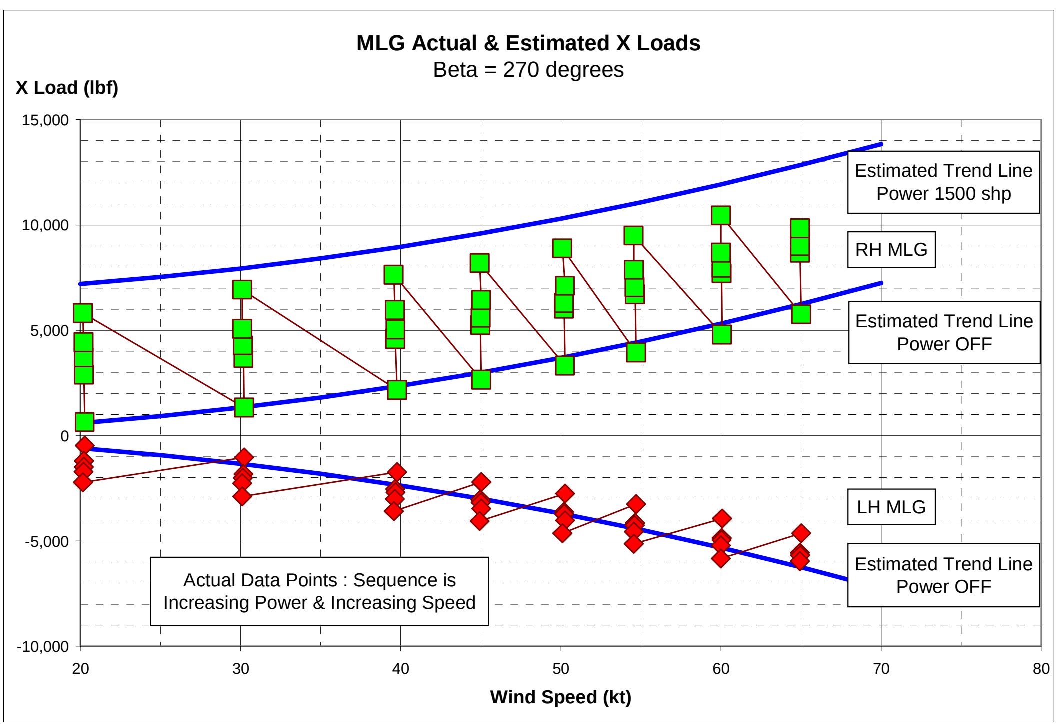

Figure 5 Y Loads applied to the MLG

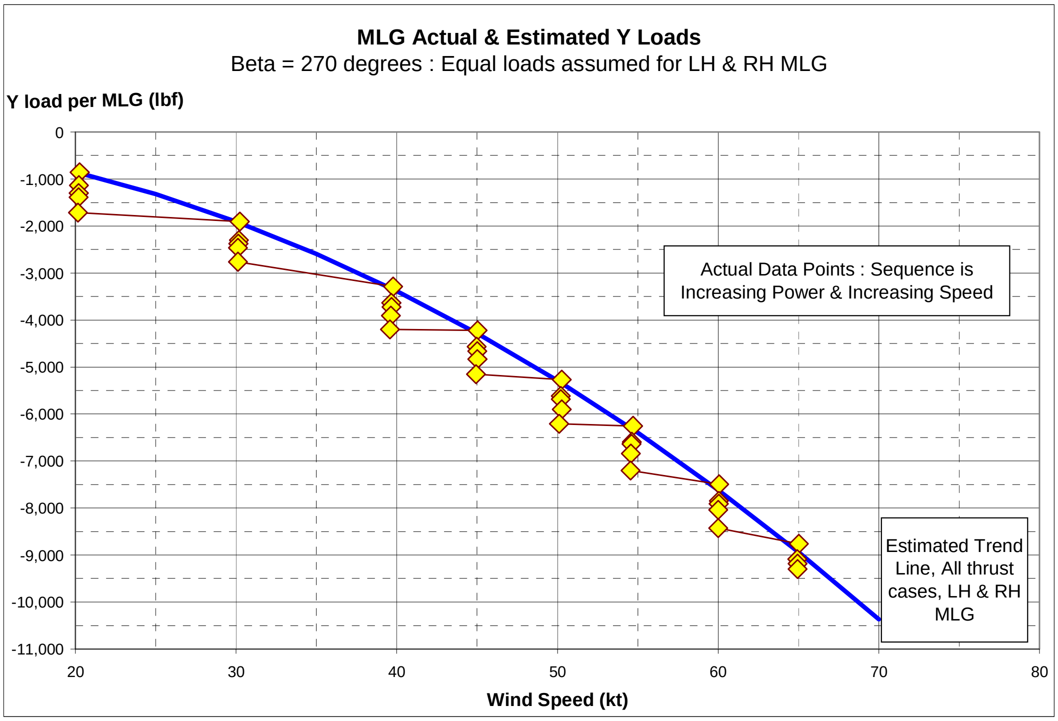

Figure 6 Yawing Moments about a point between the Left & Right MLG