AUTOMATION OF HAWKER BEECHCRAFT B200/B300 (KING AIR) AIRCRAFT - CARGO DOOR

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Abstract:
The Hawker Beechcraft B200/B300 King Air aircraft is a twin engine turbo-prop aircraft with a pressurized cabin, normally capable of carrying 9 to 11 passengers. The aircraft can have a standard air-stair style access door or an optional larger 'cargo door', with a smaller air-stair within this cargo door. In either option the door is located on the left aft side of the fuselage, just aft of the wing. The larger cargo door generally to allow greater access to the cabin for aeromedical, freight or specialty roles.

The 'cargo door' measures an opening of 52 by 52 inches (1321mm by 1321mm) and is hinged from its top edge. Operation of the 'cargo door' is carried out manually, by a single person assisted by two gas struts (not unlike those found on the lift-back on the back of a station wagon car). The door is safetied in the open position by a mechanical stay rod. The door is closed by the removal of the safety rod and pulling the cargo door down and into the aircraft fuselage, against the resistance of the two gas struts.

The operation of this large and heavy door can place the operator in is an unsafe positions and requires a level of physical fitness and effort to, especially close the door. For this reason the operation of the door is generally avoided by operators unless absolutely needed and it has also created a number of workplace injuries such as strains, falls and slips. The operation of the air-stair door within the cargo door is also mechanical, but due to the air-stair door size and weight - its operation does not pose the same safety hazards.

The engineering degree project developed an automated method of operating the cargo door, in the pre-existing cargo door installation. The design made consideration of the following:

1. cost of the installation
2. aircraft down time for the installation
3. simplicity of the retrofit installation
4. consideration of the aircraft pre-existing structure and aircraft systems
5. minimizing additional weight to the aircraft installation
6. minimizing the 'new' mechanism interfering or consuming critical cabin space
7. aircraft certification requirements, and
8. provides for the operators health and safety needs.

The automation retrofit design, was accomplished by the installation of an electrical motor, which applies it power is through a reduction gearbox, to actuate a rotary actuator and (radius) arm assembly. This, 'radius' arm controls the doors position though a slide track, affixed to the cargo door, which: extends, safeties when the cargo door open and retracts the cargo door closed. The design incorporates a self braking and position monitoring system, along with a manual method of door actuation, if there is no electrical power is available or the electric motor has failed. All of the cargo doors' original design features, including locking system, remain unaffected, except for the removal of the two side gas assist struts which are replace by this modification and (radius) arm assembly.

Key Words: Automation 'King Air' aircraft - cargo door

Introduction

The Hawker Beechcraft B200/B300 King Air aircraft is a twin engine turbo-prop aircraft with a pressurized cabin, normally capable of carrying 9 to 11 passengers. The manufacture produces the aircraft with a standard 'airstair' style door on the aft left side of the fuselage. This door opens outward and downward to provide two functions, that of: a pressurized door to the aircraft and as a set of extendable stairs to allow egress to the aircraft, refer figure 1 and 2.

The King Air aircraft can also be fitted with a larger 'cargo door', which takes the place of the conventional (manufacturers) airstair door, while incorporating its own smaller airstair door. The larger 'cargo door' generally to allow greater access to the cabin for aeromedical and freight operations. The cargo and smaller airstair door assembly is normally retro-fitted to the conventional aircraft at manufacture or later as a modification to the aircraft, refer figure 3 and 4.

The cargo door installation measures an opening of approximately 52 by 52 inches (1321mm by 1321mm) and is hinged from the doors top edge and therefore opens outward and upward. Operation of the Cargo Door is carried out manually by a single person assisted by two gas assist struts (not unlike those found on the lift-back on the back of a hatchback or station wagon style car). The door is safetied in the open position by a mechanical stay rod. The door is closed by the removal of the safety rod and pulling the cargo door down and into the aircraft fuselage, against the resistance of the two gas struts.

The operation of this door can place the operator in is an unsafe positions and requires a level of physical fitness, especially to close the door. The difficulty in closing the cargo door is further increased in warm weather which causes an increase in pressure within the gas assist struts, making it more difficult to close. The operation of the door is generally avoided by operators unless absolutely needed due to these difficulties and has created a number of workplace injuries such as strains, falls and slips. The operation of the airstair door within the cargo door, is also mechanical, but due to the airstair door size and weight - its operation does not pose an operational safety issue.

The objective of this degree project is to retro-fit an alternate method of the cargo door's operation into the preexisting installation making consideration of the following:

1. cost of the installation
2. aircraft down time for the installation
3. simplicity of the retrofit installation
4. consideration of the aircraft pre-existing structure and aircraft systems
5. minimizing additional weight to the aircraft installation
6. minimizing the 'new' mechanism interfering or consuming critical cabin space
7. aircraft certification requirements, and
8. provides for the operators health and safety needs

Proposed design difficulties/considerations

The retrofitting a design can provide many difficulties and limitations that are not always encountered in an initial design concept. This particular design is complicated by the initial design does not readily lend itself to automation due to the lack of suitable locations to easily fit actuation systems.

A major consideration of this modification is to adapt this modification design to the preexisting door with as little changes to the original configuration as possible. This reduces any effect to initial type design status of the aircraft.

Due to the size of the aircraft, weight of the installation is a major consideration. The initial aim of the modification is to not add any more then 10kg (22lbs), but ideally have the system weigh about 7kg.(15.4lbs).

The system needs to have an alternate form of actuation for 3 reasons, being:

1. The aircraft, itself, is generally not fitted with any form of additional or auxiliary power source while the engines are shut down. The aircraft can have additional ground power applied, if the ground facilities exist, but these are not always available. Some aircraft have an additional auxiliary battery fitted which is used to support ancillary systems, but this is more commonly the exception then the norm on these aircraft. Due to the electrical constraints of the aircraft and the limited capacity to operate ancillary systems, such as this door, an alternate mechanical method of actuation may be desired on occasion by some operators.

2. The King Air is commonly used in aeromedical operations where the operation of the aircraft is critical to peoples well being. For this reason, if there is a failure of the electrical portion of the cargo door actuation mechanism – there needs to be an alternate means of operation to allow patient egress.

3. When the aircraft is in maintenance, the cargo door my need to be operated without electrical power being available on the aircraft.

The lack of ancillary aircraft systems, other than electric, reduces the options that can be utilized in design of the cargo door automation system.

Attempting to develop a design based without having to manufacture specialized components which add cost and complexity to the design, rather than using generic components.

Ensuring that the cargo door operating system, will not load (or effect) the cargo door when in the closed, locked and with the aircraft pressurized.

The mechanism has a form of safeting the cargo door in the open position.

Design options
The automation of the cargo door requires a method of assisting or operating both the opening and closing of the cargo door. Four options were considered, including linear actuators simply replacing the pre-existing gas struts and also mounted across the ceiling of the aircraft and one electrically operated 'scissor link' linear actuator system mounted to either the cabin floor or lower side wall/door opening area. All of these design options were rejected due to: aircraft structural reasons, the cabin space that these methods of actuation and mechanical difficulties.

Selected design
The selected design is an electrically powered system, which drives through a geared rotary actuator located/mounted on the internal side wall of the aircraft, a 1.242 meter long 'radius arm'. The 'radius arm' rotation controls the position of the cargo door, in both the opening and closing directions. The actuation force of the radius arm, is applied through to the door via the 'radius arm-track' (track), affixed to the door structure. The track allows for the changes in geometry between the arc of the cargo door and the arc of the radius arm. Refer to figure 5. The arm and the track have a method of positive contact throughout the doors operating range so provide for the safety needs. Refer figure 6.

This concept, of this selected design, best fulfills the consideration requirements most importantly the mechanism consumed as little cabin space as possible and is relatively simple in its operation.

Design process
After recognizing the need for the design and deciding on the concept of the 'radius arm' mechanism, the following was the design process.

1. Calculating the loads and forces applied by the door and how they would affect the drive mechanism and mounting structure, including dynamic forces.
2. Selecting the motor and gearbox assemblies, according to the loads applied
3. Designing the 'radius arm' and 'radius arm-track'
4. Designing gearbox/motor mounting.

The design factor of safety (Kf) in this design is 1.5. The justification for this is that the cargo door operation is not critical to the safe operation of the aircraft. It is purely a supplementary system to the aircraft.

Calculating forces
After selecting this 'radius arm' design, to operate the cargo door, based on elementary values of the door operation, accurate values had to be established. This process was essentially divided into four steps, in the following order:

1. Establishing the known reference points and angles of the cargo doors operation which all calculations could be based. Refer figure 7.
2. Calculating the moment values applied by the weight of the cargo door to the hinge of the cargo door, over its entire operating range. Refer Table 1.
3. Calculating the position, of the radius arm on the radius arm-track and the forces applied to the arm throughout the doors travel. Refer to Table 1.

4. Calculation of the range of radial and shearing forces applied to, the 'radius arm', gearbox and motor. Refer to Table 1.

Radial forces - are compressive, on the radius arm, throughout the doors operating range.
- the largest compressive force is applied at the cargo door 101 degree angle (fully open) position.
- the maximum Radial force, on the radius arm, is 93.6N, with a rotational force of 68.7N.

Rotating force - are all in the negative direction throughout the doors operating range (naturally closing the cargo door closed)
- the largest rotating force is applied at the cargo door 45 degree angle position.
- the maximum rotating force is 109.4 N, with a compressive force on the arm is 60.7Nm. This force applies a 135.9Nm torque at the gearbox output shaft.

Electric motor and gearbox - selection.
The retro-fit design uses preexisting commercially available electric motor and gearbox assemblies. Use of these pre-existing components allows for simplicity and cost effective along with ease and cost effective future maintenance these components. The size of the motor and gearbox output shaft diameter is dictated by the peak torque and radial loads being applied to it by the cargo door. The gearbox output shaft diameter then dictates aspects of the radius arm design.

The motor/gearbox assembly selection was based on the following constraints:

- 24VDC electric motor – due the electrical power constrictions of the aircraft
- a gearbox, thence motor, maximum normal operating torque limitation of 135.9Nm.
- a gearbox that permits a radial load greater than 93.6 N

Using these constraints the following motor gearbox assembly was selected, from a particular vendor (refer figure 8):

- 28VDC motor rated at 2500 RPM when combined with the selected gearbox, will draw 5 amperes during its peak operation.
- coupled with a failsafe brake unit, that has a spring applied friction brake that is released when electrical power is applied to the motor.
- the motor is also coupled with an encoder that provides an adjustable internal position limitation control to the motor.
  - This would be set to slow then shut off the motor at the full extension and closing positions of the doors operation.
  - The use of the motor encoder removes the need for additional door operation control witches and sensor needing to be installed on the cargo door itself.
- the gearbox is a 1:400 ratio unit with a normal operating torque limitation of 164.7Nm and a peak maximum torque of 257.4Nm (within the factor of safety limit of 203.8Nm)
  - the gearbox output shaft is 12.8mm (0.5in) diameter
  - with a No.606 Woodruff key drive shaft.

Electric motor and gearbox – mount design
As the suitable engineering information about the aircraft structure is unavailable for this project, a full design of the motor/gearbox mount is not provided, except for the concept design.

The mount would be a suitably made to adapt to the aircraft internal side wall and cargo door aperture structure. It would be in the same position and eventually taking the place of the current fitting for the gas-assist strut for the cargo door.

The mounting structure would attach to the gearbox portion of the motor/gearbox assembly. This would allow for the removal and replacement of the electric motor (the most likely part of the design that would need to be replaced or regularly overhauled) without having to affect the safety or operation of the remaining door operating system.

'Radius arm-track' – design (Refer figure 9)
The design of the radius arm and the track has to for fill the following limitations:

- maximum width of the track being 50mm to fit within the preexisting clearance between the cargo door and the door frame aperture.
- a positive control and connection between the 'radius arm' and 'radius arm-track' to ensure that under normal operation the arm and door do not become disengaged from each other.
- able to withstand the maximum rotating load applied to the 'radius arm' of 216N.

The design of the 'radius arm-track' is essentially a 500mm (19.6in) long inverted 'U' shaped channel in which the roller bearing, connected to the 'radius arm', runs to transmit the loads between the cargo door and the actuator drive. This track is rigidly connected to the cargo door by the use of two 6.4mm (0.25in) bolts. These two bolts also serve two needs to attach the track to the door and as a mechanical means preventing the 'radius arm' bearing from inadvertently extending beyond the track limits. The two bolts have an external bushing installed over them and between the two inner faces of the channel to provide strength and rigidity to the track. One side of the track has an elongated cut out for the for a guide bolt, from the radius arm bearing, to travel along, to ensure a method of positive contact throughout the doors operating range. This safeties the 'radius arm' to the 'radius arm-track'.

The 'radius arm track' is has a range of forces applied to it over the cargo doors' operation. The largest is 216N when the cargo door is at 45 degree angle, at which point the 'radius arm' contact point is essentially 50mm from one end of the 'radius arm track'. This force is applied in the centre of the channel with the force distributed through the side walls of the channel and carried into the cargo structure by the two bolts previously mentioned.

- The resulting loads applied at each bolt location, are: Bolt 'A' 22.5N and Bolt 'B' 194.0N.
- The selected 6.4mm (1/4in) dia. bolt for the installation will need support a τave = 2.75MPa.
- The 'radius arm-track', with 3mm side walls, will need be manufactured of a material that can withstand a shear stress of 1.52MPa.

‘Radius arm’ – design
The radius arm is a 1292 mm (50.9in) long arm (with an effective length of 1242 mm (48.9in)) that provides the drive from the motor/gearbox to the radius arm-track, attached to the cargo door. The arm is attached to the gearbox output shaft via Woodruff key installation. The contact point between the ‘radius arm’ and the ‘radius arm-track’ is made through a 60mm diameter roller bearing which is attached to the radius arm and rolls along the track. Refer figures 10.

The radius arm was designed under the following specific requirements:

- the 12.8mm (0.5 inch) drive shaft and the No.606 Woodruff key provided by the shaft manufacture.
- the maximum sheering load applied to the ‘radius arm’ of 109.4 N
- the maximum radial compressive load applied to the ‘radius arm’ of 93.6 N
- the maximum torque load applied to the ‘radius arm’ at the gearbox shaft is 135.9 Nm
- maximum width of the arm being 42mm to fit within the internal dimension of the radius arm track.

Bearing installation.
The bearing is installed by a single through bolt in the radius arm. The bolt passes from the outside of the ‘radius arm track’ through a bushing and the slotted track in the ‘radius arm track’, through one side of the forked end in the ‘radius arm’, then the bearing, finally being secured through the second side of the fork. Ref figure 6

Radius arm.
The radius arm is designed as a modified “I” style beam. The web sections extending to the full width of the arm (43mm) at the fork end to provide for the bearing installation and also at the drive shaft attach end to allow maximum contact area with the key drive, refer figure 10. As the maximum stress is located at the drive shaft connection, the design of the main section of the arm would be calculated to below these stress limitations.

The general profile of the radius arm, except for the drive and bearing attachments, is shown in figure 11.

The maximum stress in the radius arm is located at the drive key area where the gearbox drive shaft attaches. Material selection for the radius arm, is based on these stresses.

Cargo door actuation system
The automated cargo door operation will be accomplished by either one of two methods. Normally, the door would be opened and closed using a selection switch mounted on the aircraft cabin side wall. The selection switch would be connected in series with a master switch and electrical circuit protection devices used and standard aircraft electrical designs. The door would be powered from a hot DC bus within the aircraft from the aircraft battery or a supplemental DC system. Alternately operated through a mechanical adaptor with the use of a (standard tool) 3/8 drive ratchet wrench through the brake unit, mounted on the top of the electric motor.

The cargo door actuation system can be manufactured using the proposed design (section 5.4.1) and complying with the limitations imposed by the pre-existing aircraft design. The estimated total weight of the installation is 11.73kg (25.8lbs) less the estimated weight of removed aircraft component due to the modification, the total weight increase per aircraft is estimated as 10.75kg (23.6lbs). Refer Table 2.

The radius arm actuation mechanism, consumes an additional cabin space of approximately: 330mm (13in) longitudinally, 80mm (3.1in) vertically and 80mm (3.1in) laterally. This area is located on forward side wall of the cargo door opening, located 1100mm (43.3in) from the aircraft cabin floor.

Project design limitations

Information of the pre-existing aircraft structure is not readily available therefore a full adaption of the modification cannot totally assessed. Although every attempt was made in the designed modification, to place loads in know pre-existing load bearing locations it is reasonable that modification can be adapted to the aircraft.

References

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[2] F.P. Beer etal, *Mechanics of Materials*, McGraw Hill, 2009

[3] F.P. Beer etal, *Vctor Mechanics for Engineers Statics and Dynamics*, McGraw Hill, 2007

[4] Hossein Rahemi, *Finite Element with Matlab Application*. Vaughn College of Aeronautics and Technology, 2006.

Figure 1 – **Airstair door location**

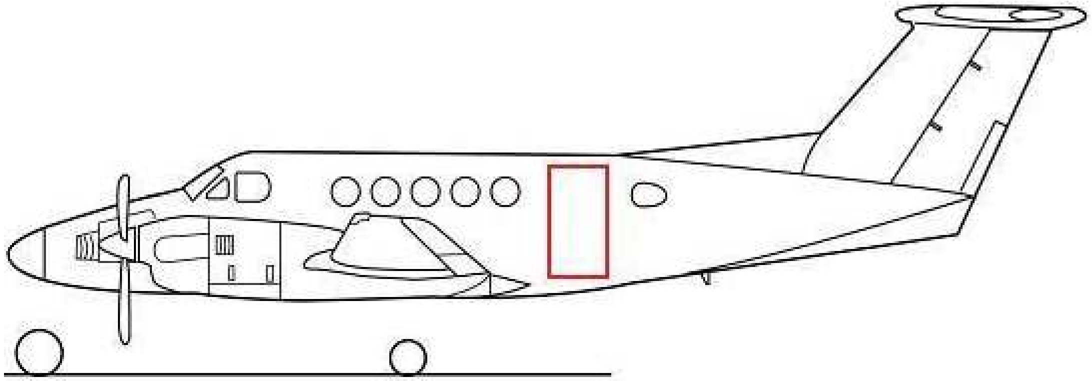


Figure 2 – **Airstair door** (open)

Figure 3 – Shows the size and **location of the (larger) cargo door**, with the smaller airstair door located within the cargo door.

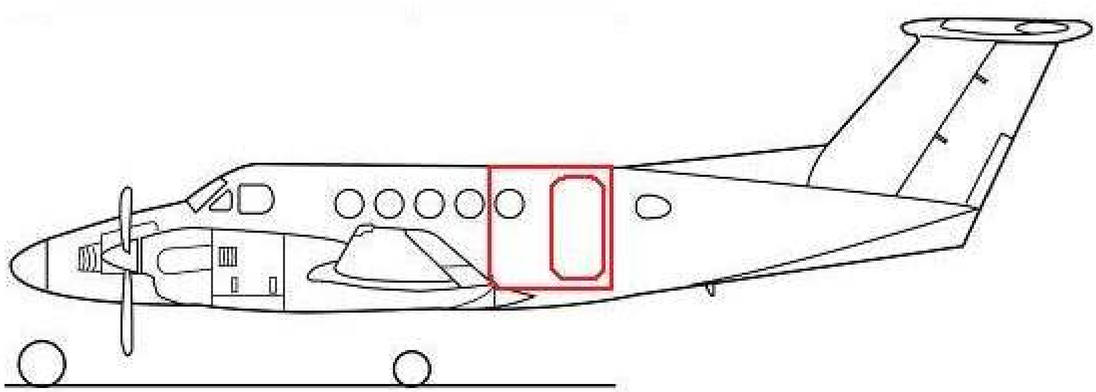


Figure 4 – Cargo door (open).

Figure 5 – 'Radius arm' design

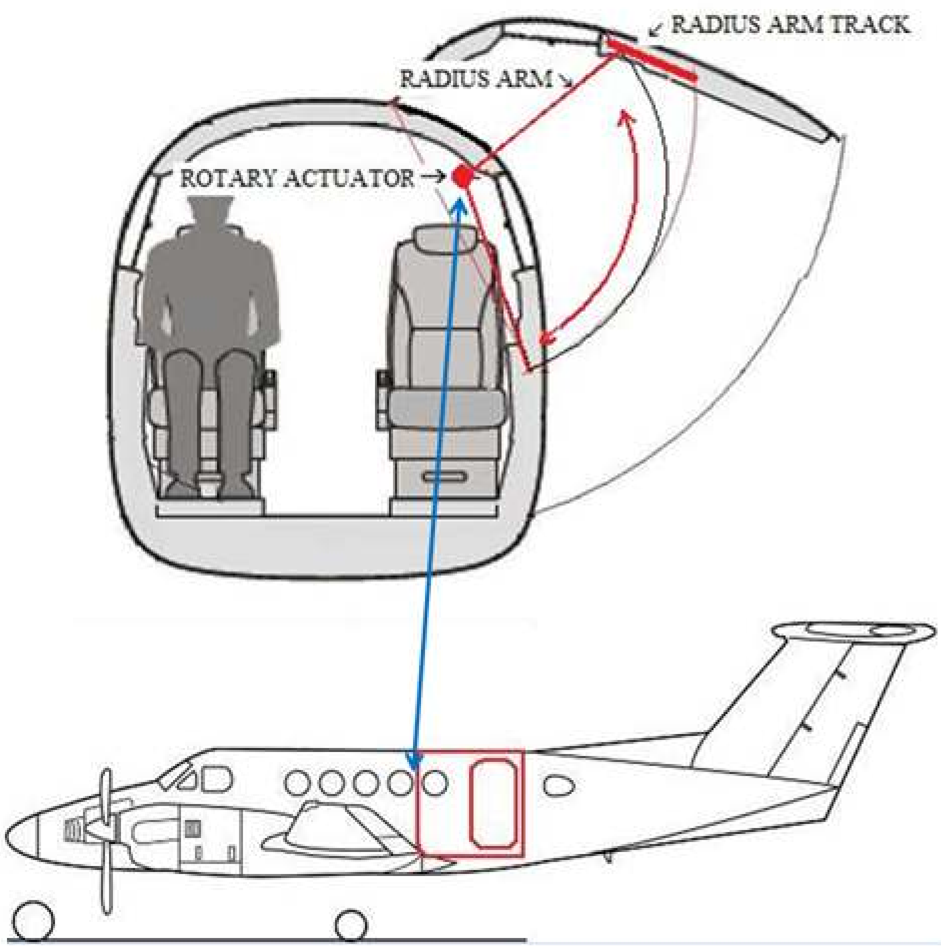


Figure 6 – Radius arm assy

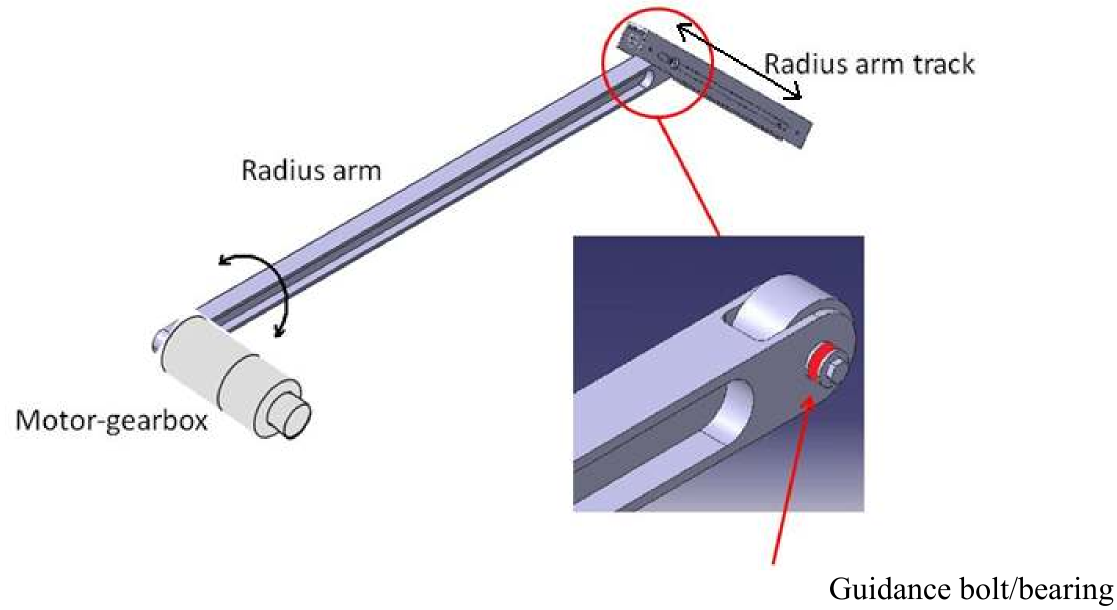


Figure 7 – Reference points for calculations

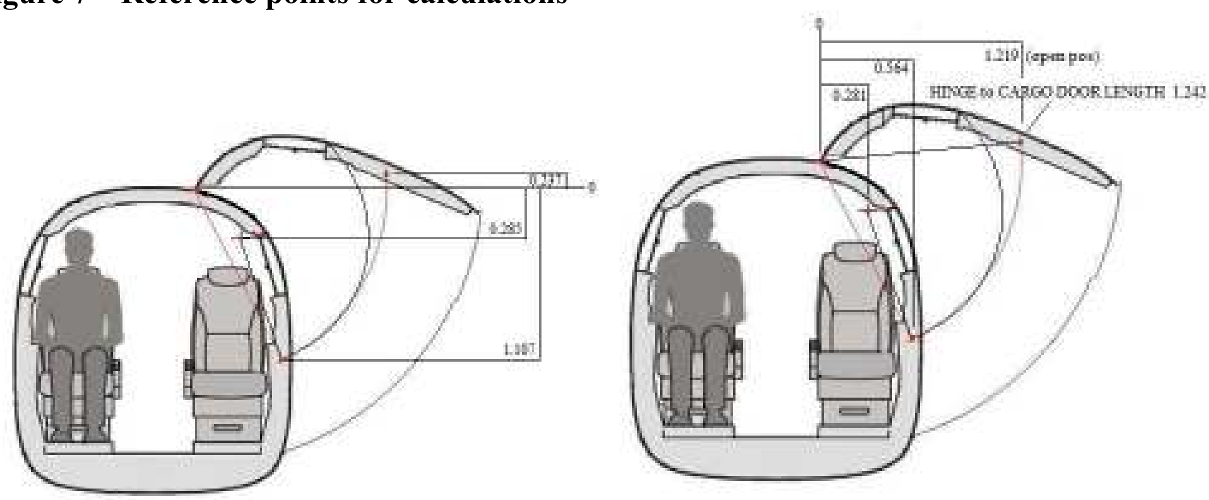


Figure 8 – Electrical motor/gearbox (rotary actuator) unit

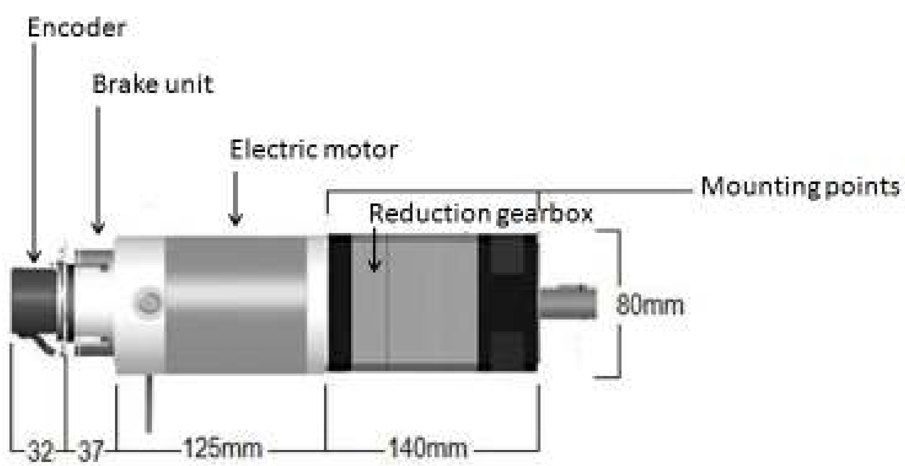


Figure 9 – Radius arm-track

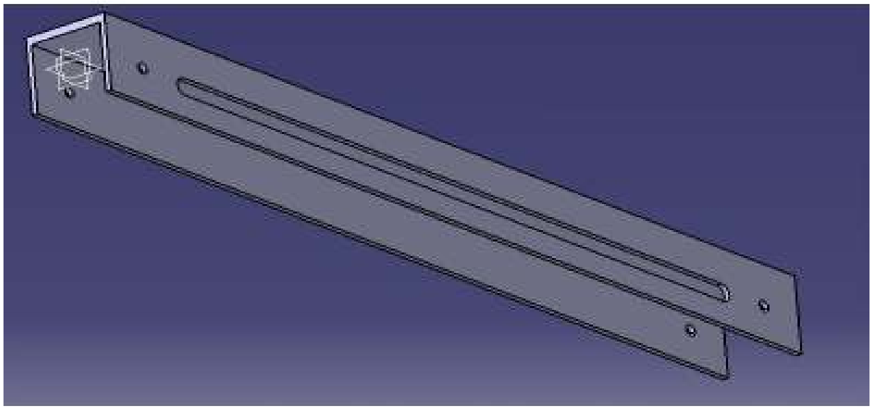


Figure 10 – Radius arm

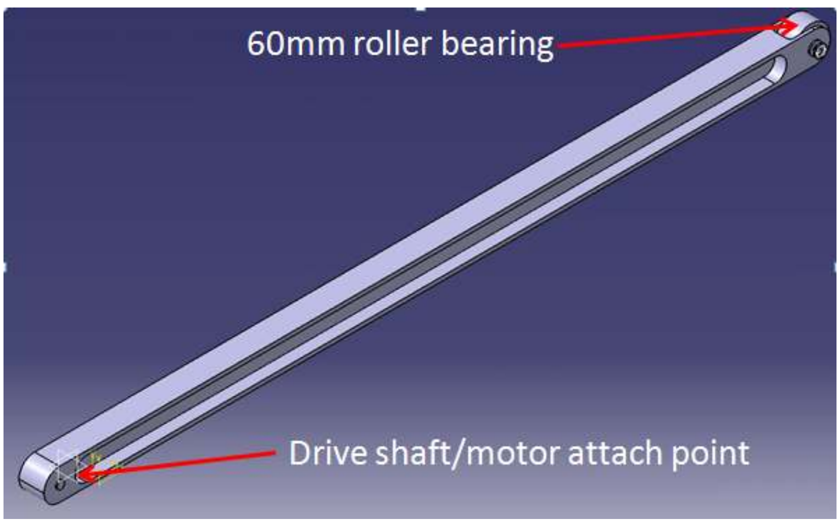


Figure 11 – Radius arm – cross-section

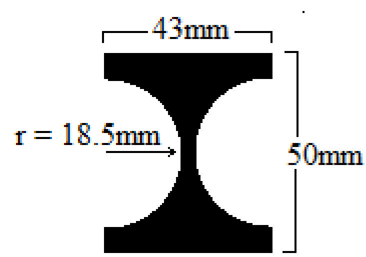
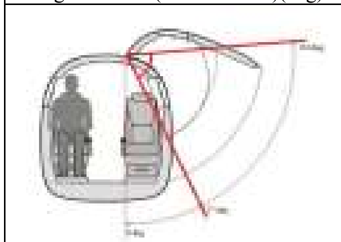
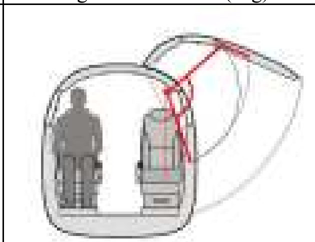
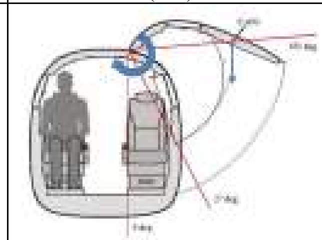
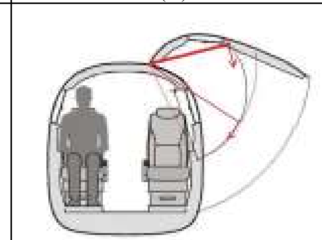
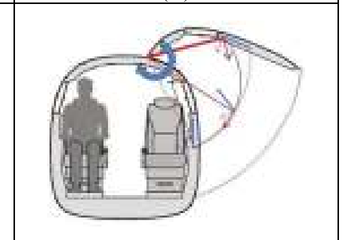


Table 2 – Weights

Item	**weight**
motor/gearbox/encoder	4.21kg
radius arm assy (inc bearing) (Aluminum Alloy 6061T6)	6.23kg
radius arm track (Aluminum Alloy 7075T6)	0.79kg
wiring and hardware	0.50kg
TOTAL WEIGHT of installation	11.73kg
less removed components from aircraft (approx)	1.00kg
Effective weight of modification	**10.73kg**

Table 1 – Moment and load calculations

ANGLE OF DOOR	ACTUATOR ARM ANGLE	MOMENT APPLIED TO DOOR HINGE BY DOOR WEIGHT	FORCE OF DOOR: APPLIED AT ACTUATOR CONTACT POINT	COMPRESSIVE FORCE APPLIED TO RADIUS ARM
hinge to CofG (from vertical)(deg)	angle from vertical (deg)	(Nm)	(N)	(N)
				
27	19	250.91	203.66	176.38
28	20	253.20	205.15	177.66
29	21	255.61	206.73	179.04
30	22	258.14	208.43	180.51
31	24	260.81	209.91	181.79
32	25	263.62	211.86	183.47
33	27	266.56	213.63	185.01
34	28	269.66	215.83	186.91
35	29	272.92	218.17	188.94
36	31	276.34	220.40	190.87
37	32	279.93	223.04	193.16
38	34	283.70	225.63	195.40
39	35	287.67	228.59	197.96
40	37	291.84	231.56	200.54
41	38	296.22	234.89	203.42
42	40	300.83	238.29	206.37
43	41	305.68	242.03	209.60
44	43	310.78	245.91	212.96
45	44	316.16	250.10	216.59
46	45	310.78	245.80	212.87
47	47	305.68	241.73	209.34
48	48	300.83	237.90	206.03
49	50	296.22	234.31	202.92
50	51	291.84	230.89	199.96
51	53	287.67	227.74	197.23
52	54	283.70	224.69	194.59
53	56	279.93	221.93	192.20
54	57	276.34	219.22	189.85
55	59	272.92	216.82	187.77
56	60	269.66	214.40	185.68
57	61	266.56	212.13	183.71
58	63	263.62	210.19	182.03
59	64	260.81	208.18	180.29

60	66	258.14	206.53	178.86
61	67	255.61	204.77	177.33
62	69	253.20	203.39	176.14
63	70	250.91	201.85	174.81
64	72	248.73	200.73	173.84
65	73	246.67	199.40	172.69
66	75	244.72	198.53	171.93
67	76	242.87	197.40	170.95
68	78	241.12	196.75	170.39
69	79	239.47	195.81	169.58
70	81	237.91	195.39	169.21
71	82	236.44	194.63	168.55
72	84	235.06	194.42	168.38
73	85	233.77	193.84	167.87
74	87	232.57	193.85	167.88
75	90	231.45	194.52	168.46
76	93	230.40	195.39	169.21
77	94	229.44	195.19	169.04
78	95	228.55	195.06	168.92
79	98	227.74	196.33	170.02
80	99	227.01	196.38	170.07
81	101	226.35	197.22	170.80
82	102	225.76	197.44	170.99
83	104	225.24	198.50	171.91
84	105	224.79	198.89	172.24
85	107	224.41	200.17	173.35
86	109	224.11	201.58	174.57
87	110	223.87	202.24	175.14
88	112	223.70	203.88	176.57
89	113	223.59	204.72	177.29
90	115	223.56	206.61	178.93
91	116	223.59	207.63	179.81
92	117	223.70	208.74	180.77
93	121	223.87	213.17	184.61
94	122	224.11	214.53	185.78
95	123	224.41	215.97	187.04
96	125	224.79	218.72	189.41
97	126	225.24	220.38	190.85
98	128	225.76	223.43	193.49
99	130	226.35	226.66	196.30
100	131	227.01	228.70	198.06
101	133	227.74	232.27	201.15