

Challenges Associated with a Complex Compound Curvature Passenger Doors

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ABSTRACT

This study investigates challenges associated with integrating a passenger (PAX) door on complex compound curvature (CCC) fuselages. Aerospace companies are investigating concepts that no-longer have constant cross-section (CS) fuselages.

The PAX door is based on a generic semi-plug door for a long range business jet (BJ). This study investigates limitations of locating the door by varying the transition zone angle. A parametric CATIA tool, coupled with the use of finite element model (FEM) results can highlight key drivers in the design and location of PAX doors, creating a first-draft structural layout. The associated impact on the design and structural architecture for a fold down PAX door with integrated stairs is discussed.

The impact of CCCs on the PAX door design is investigated with consideration to location, kinematics and function of the door. Design requirements, when coupled with stress analysis to simulate pressurization effect of the load applied to the stops, can create a powerful tool. Combining the architectural layout, design requirements and top-level stress analysis can be used to define limit curves and understand key design drivers that impact the door position, with reference to weight, design and human factor constraints.

The design conclusions to-date suggest for a transition angle above 5 degrees, the structure is too complex to use a traditional frame and lintel design and will be an interesting case for bird impact. Below 5 degrees is the limit for conventional door and kinematic designs in-line with frames.

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INTRODUCTION

The aerospace industry has made a great deal of innovations in the past few decades. New and exciting concepts and technology proposals have seen the release of market driven airframes to meet environmental and economic goals. Some of the most exciting new concepts released within the public domain have enlightened aero-enthusiasts with configurations that claim to change the industry standard to meet, if not exceed future environmental and cost drivers, as described by [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] inclusive. Many of these concepts explore game-changers that fall in the commercial or freight markets for wide, narrow-body and BJ categories, as shown in [Figure 1](#).

Despite all the new concepts, current aircraft face the same challenges of CCC fuselages, such as the C-Series, A350 and B787. The PAX doors are located in a transition

area between the cockpit and fuselage in a CCC area. The challenge faced is, how close to the cockpit can the PAX door be, without compromising the weight of the aircraft?

Anticipating the market is an area of focus for the Advanced Design (AD) group in Bombardier Aerospace. In support to AD, the Advanced Structures (AS) group develops structural concepts, assess feasibility for design, stress and weight targets, and identify structural items that may prove challenging or of high risk to the aircraft level concept.

With this in-mind, the AS group, realize that the market trend for more unconventional aircraft shapes could be an area of exploration by AD for future products. Therefore in a bid to anticipate future challenges and support AD to close knowledge gaps, the author decided that one of these areas could be the design, kinematics and stress assessment of a PAX door and proposed the development of a new tool to assess this. The objective of this tool was to understand current limitations, explore the design space and create limit

curves to assist AD to develop their multi-disciplinary design optimization (MDO) capabilities to include structural considerations.



Figure 1. Unconventional future aircraft concepts - various sources [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] inclusive.

Having studied many of the market drivers for the NASA N+ programs, the author understood that the market, whether for BJs or wide-bodies has a continuing trend to increase the width of the PAX cabin for increased comfort level. Increasing the fuselage width and combining this with a conventional cockpit leads to changes in the general structural architecture. One key structural area affected by the change in cabin width is the PAX door region. The challenge, all-be-it structural, also has implications to the kinematics, function, human factors and aesthetics.

The paper here-on will discuss the challenges and requirements set for the PAX door study, followed by the methodology used to create the two versions of the PAX door tool. A brief discussion into the design, kinematics and structural configuration enables a good basis before analyzing the impact of CCC on these aspects as well as considering stressing the structure. The stress analysis will be a further addition to this study and is not included within this paper. The analysis of stress will allow the reader to comprehensively understand the outcome of the design drivers highlighted within this study and is considered as further work.

THE CHALLENGE

Anticipating a new design concept to be released from AD is a challenge, and trying to understand implications on the structural design of an unknown vehicle becomes a near-

impossible task. In order to provide a better understanding to the reader, the following process was used.

The main challenge and complexity comes from defining the fuselage shape and identifying a baseline; which was selected to be a long range BJ. Using the simplified sketch (Figure 2), we can distinguish the three distinct regions of the forward fuselage into zones; the cockpit, transition and constant cross-section (CS) zones.

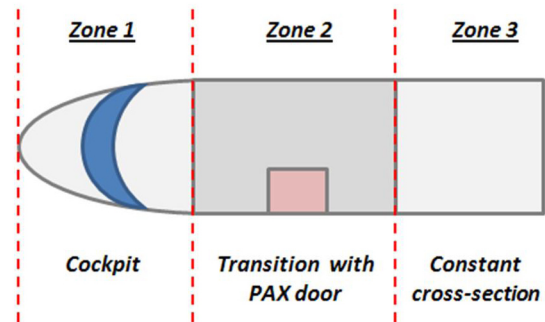


Figure 2. Representation of forward fuselage zones.

What is a CCC PAX Door?

Compound curvature is defined as a “combination of two or more simple circular curves of different radius having their curvature in the same direction. Also, a curve that is made up of a series of successive tangent circular arcs is called a compound curve” [19]. A compound complex curvature (CCC) adds to the complexity of the compound curve by adding another direction of curvature, whether it is a more extreme curve, or a complete change in direction. This limits where the PAX door can be located on the fuselage. This is key to understanding how the study can be used to understand the impact of curvature on the PAX door transition zone curvature, as shown by Figure 3.

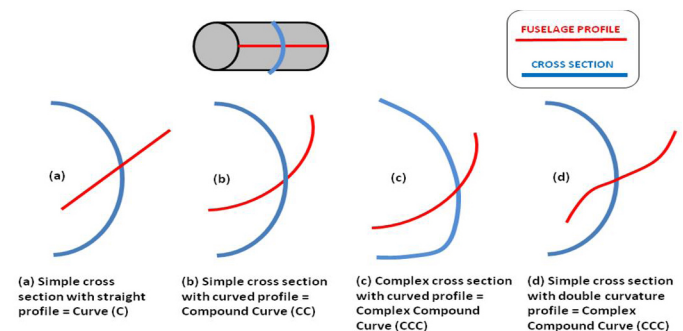


Figure 3. Visual representation for context behind CCCs.

The PAX door is located within the transition zone (zone 2), as shown by Figure 2. At the intersection between zone 1 and 2, the shape is a fixed with a circular CS. Between zones 2 and 3 is the area that has a variable CS. Therefore the internal cross-section of zone 2 needs to be able to morph to

create a smooth transition into the constant section fuselage. If zone 1 was circular, and zone 3 was non-circular, then the change in fuselage curvature within zone 2 will create a CCC, and this will impact the PAX door design, kinematics and surround structure.

Challenges associated with CCC PAX doors, is an area of Aerospace that is highly integrated between the structures, systems, human factors and customer focused groups. This is a topic that is applicable to any aircraft, regardless of size or type. A key note for the reader is that although CCC fuselage PAX doors exist today, the weight impact associated have not been quantified from a weights perspective. This is why most of the time work packages are fighting to achieve their weight targets and often struggle because the knowledge was not available at the time to create a realistic weight assessment. In order to determine realistic weight targets, the impact of various design, stress, kinematics and functional requirements that impact the door surround and stiffness must be considered early on in the structural concept development.

The author has found little to no references of published papers within this domain - identifying a knowledge gap. This is especially true for smaller jets, where this complexity is increased because of the small radius on the fuselage. The author re-iterates that this study is only applicable to smaller jets, where the overall diameter of the fuselage creates the CCC challenge for the PAX door.

What are the Constraints, Requirements and Considerations?

Any data presented in this study, referring to structural geometry or dimensions, refers to that of a long range BJ. The design and kinematics of the door latching mechanism, uses the design of a semi-plug-type door.

The author advises caution when using any data contained within this publication because it is configuration specific to smaller, BJ classifications, and will not be applicable to larger wide-body airframes.

Fuselage structure

The starting geometry for fuselage dimensions, flat floor height-to-ground, and PAX door geometry were extracted from the baseline aircraft. A number of requirements and constraints were set to initiate this study:

- PAX door is located on the port side
- no service access door opposite on starboard side
- PAX door has integrated stairs; the first and last steps are folding steps on the door
- Fuselage height is fixed at 106 inches
- Fuselage width is variable (by varying the transition zone angle, α - see [Figure 6](#))
- Flat-floor height to ground is fixed at 70 inches

The nose starts at fuselage station 0 (FS.0). The bulkhead that separates the cockpit from the PAX cabin is fixed at FS.

120; 120 inches from the nose and defines zone 1, the cockpit. Zone 2 is the transition region containing the PAX door & surround structure. The length of the zone 2 spans 7 frames, with 16 inch frame pitch extending to FS.232. Zone 3 beyond FS.232 represents a constant CS fuselage.

PAX Door type & location

The door is a semi-plug configuration that pivots at the lower edge of the door on a goose-neck hinge-line. The door has integrated stairs and telescopic handrails, which are constraints, set by the business jet configuration. When fully closed the door is held in place by 6 parallel door stops on either side. The exact kinematics includes a series of translations and rotations that are identical to a super-mid-sized BJ door.

The door location was offset by 38 inches from FS.120 to account for the cabin interior layout for a crew lavatory. Typically 36 inches is sufficient, but was moved a further 2 inches aft in order to position the door equidistantly between two frames in the transition zone. The door geometry was considered a type 1 oversized exit [20], [21], similar to the requirements for a long range BJ.

PAX door stairs

The PAX door stairs are a challenge because of human factors concerns and the fuselage shape. In order to establish the design constraints of stairs, the author used the civil construction criteria [22], in order to create a realistic design.

The main concern for the stair design is to avoid the possibility of trips or falls. As a general rule-of-thumb, the distance between each step must be the same height. There are two exceptions to this rule, the first step onto the stairs and the last step into the aircraft. The last step before entering the aircraft is a function of the height of this step relative to the cabin flat floor. There must be sufficient height available in the cabin for a 6 foot male to enter the cabin without hitting any of the surrounding structure or interior finishing. This last step usually has a larger tread length, and therefore the height difference between this last step and the flat floor is not considered a concern at an early concept stage.

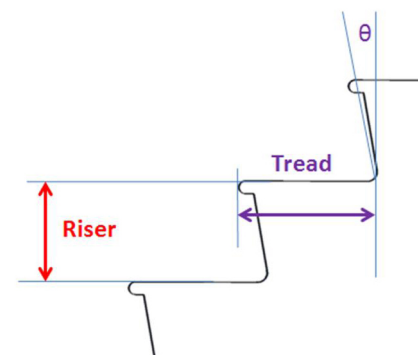


Figure 4. PAX door stairs: visual representation of step, riser and orientation angle used for the tool development.

The number of steps integrated into the door is driven by the angle of the door and the distance between the first step and the ground. Since the ground height is fixed, the only variables are the door rotation angle and the curvature of the door. When open, the door must not contact the ground, and maintain a clearance of 4-6 inches. The door rotation angle depends on the curvature of the door, which is a function of the CCC at the fuselage transition zone. The angle also defines the step tread and riser, which for this study are considered constants as well as the orientation angle (θ), as shown in Figure 4.

There are a number of assumptions that have been made in order to model the tool to create a parametric digital mock-up (DMU) within CATIA v5, and these are:

- Minimum FAR stair width is 22 inches
- Maximum model stair width is 28 inches
- Tread (length) is fixed at 8.9 inches
- Riser (height) is fixed at 8.1 inches
- Back orientation angle θ is fixed at 10 degrees.

Telescopic hand-rails are modeled within the tool to illustrate their location relative to the stairs. The function of the handrails also follows civil building standards. The kinematics of the handrails is as per the super-midsized BJ, but resembles the geometry of the long range BJ handrails.

The stairs are certifiable to FAR part 91, where for this class of vehicle and exit, there are no requirements for any passengers with disabilities and a 66% survivability rate in the event of an incident. There is one requirement that is not addressed by this paper. This reflects a worse-case scenario where a maximum of 7 degree angle to the ground is achieved by a single main landing gear failure. This case is not considered for this study and may be investigated in the future.

PAX door surround structure

The baseline structure surrounding the door consists of metallic frames at 16 inch pitch, with 2 frames either side of the door. There are 2 upper and 2 lower intercostals surrounding the door, more commonly referred to as lintels. The lintels assist with the load transfer around the door-cut-out and this helps transfer the load because 2 of the frames are cut to accommodate the door opening in the tool. Figure 5 shows a typical structural layout of a super-midsized BJ door surround, where only 1 frame is cut for the door cut-out. Lintels usually continue at least 2 frames down into the structure so that the load can be dissipated; in some designs they do not end but transition into stringers.

The PAX door surround structure uses a torque box methodology to transfer the pressurization load around the door cut-out. As well as the surrounding structure there are sometimes intercostals located on the door sides that run longitudinally (parallel to the aircraft X axis). These intercostals are strategically located to transfer loads induced

on the structure from the door stops. Each door stop transfers load through the intercostals and into the door surround torque box. This configuration uses inner support frames offset by 6 inches from the main fuselage frames. There are 2 lintels above and below the door cut-out, each with a 6 inch offset from one another. This is closed off with an internal structural skin to form the torque box. The structural depth of the surround is 4 inches, offset from the outer mold line (OML). There is a 2 inch gap between the surround structure and inner mold line (IML) assumed to be used for the interiors. A number of stringers were positioned radially in order to understand the impact on the stringer orientation.

As mentioned, there are 6 door stop locations positioned along the inner support door structure on either side of the door. The door stops are considered to be 0.5 inches by 0.25 inches in width and depth, with a length that protrudes by 2 inches into the door opening. These 12 stops, shown in Figure 5, are considered to take all pressure loads acting on the door during flight with an assumed target pressure of $1\Delta P$.

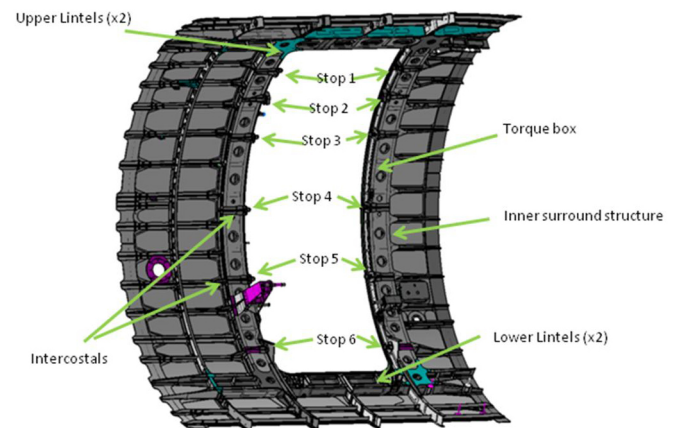


Figure 5. PAX door Surround Structure: Extract of a supermidsized BJ door structure and stop configuration.

TOOL DEVELOPMENT

The author decided to develop a parametric tool in order to visually understand the impact that CCCs have on the PAX door design process. This tool provides the ability to change the fuselage CS shape, modify the transition angle and understand the impact on the structure. The tool would comprise of the 3 zones previously described, with a single parameter to drive the study: the transition zone orientation angle (α), as shown by Figure 6.

In an effort to break down the study into manageable segments the author, under advisement by peers and knowledge owners, created a plan to rationalize development steps for this tool. The proposed plan involved simplifying the transition zone into 3 separate studies using a (a) linear, (b) compound, and (c) complex transition zones (as per Figure 3). The aim was to quantify the structural impact on each of these configurations by changing α ; in order to