

UNCERTAINTY QUANTIFICATION FOR AIRCRAFT SAFETY

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Abstract

Ensuring the safety of airplane flight is an important and active arena of research in the aerospace community. Notwithstanding the research, development, and legislation aimed at certifying airplanes for safe operation, an analysis of the effects of uncertainties on certification quantities of interest is generally lacking. The central objective of this thesis is to examine and analyze problems in aircraft safety and certification from the standpoint of uncertainty quantification. In particular, two canonical problems will be discussed – the accretion of ice on an airplane airfoil/wing, and the development of a fire in a cargo hold. This work will discuss the uncertainties present in each of these scenarios and how they may be modeled, the output quantities of interest, and how the statistical relationship between the two may be approximated.

Acknowledgements

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To my parents, Kelsey Carroll, and fellow researchers.

Contents

Abstract	iii
Acknowledgements	iv
List of Tables	viii
List of Figures	ix
1 Introduction	1
1.1 Motivation and Goals	2
1.2 Approach	3
1.3 Contributions	3
2 Related Work	4
2.1 Tables	4
2.2 Figures	5
3 Usage	7
3.1 Options	8
4 Conclusion	11
4.1 Future Work	11
A Implementation Details	12
A.1 Switching Formats	12
A.2 Long Tables	12

A.3 Booktabs	13
A.4 Bibliography and Footnotes	14
A.5 Figures and Tables	14
B Printing and Binding	15
B.1 Printing	15
B.2 Binding	16
Bibliography	17

List of Tables

2.1	Thesis Publishing Options	5
3.1	Options Provided by the PУthesis Class	8

List of Figures

2.1 Sample Title Page Layout	6
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Chapter 1

Introduction

In an aggregate sense, aviation is one of the safest means of transportation that exists today. According to statistics provided by the National Transportation Safety Board (NTSB), of the 34,678 transportation fatalities registered in 2013, only 443 were related to aviation, compared to 32,719 highway-related fatalities, 891 rail-related fatalities, and 615 marine-related fatalities [2]. Ensuring the continuation and improvement of this tradition of safe airplane flight is the responsibility of the Federal Aviation Administration (FAA), which proposes legislation aimed at establishing certification rules to establish the airworthiness of airplanes.

Two longstanding phenomena that pose issues for aircraft safety are aircraft icing and cargo hold fires. Both of these problems are explicitly addressed in Title 14 of the Code of Federal Regulations (14 CFR), part 25 (Airworthiness Standards: Transport Category Airplanes). The importance of ice accretion is underscored by the recent 2014 amendment to the CFR, which enacts stricter certification rules for flight in supercooled large droplet (SLD) icing conditions [1]. The importance of cargo hold fires is demonstrated by the tight requirements for fire detection systems, which must alert the flight crew within 60 seconds of ignition [3].

Given the recognized safety issues presented by both icing and fires, there has been much research conducted in these arenas. As we will see in this thesis, the literature encompasses work that addresses informational deficiencies across a wide range of topics, including computation, experimental observations, fundamental physical understanding, sensitivity analyses/optimizations, etc.

However, both ice accretion and cargo hold fires are processes which are, in practice, subject to a wide range of uncertainty. The sources of these uncertainties are manifold, but what is important is that the existing literature lacks a thorough treatment of this topic. Stated plainly, this is the central objective of this thesis – to address the topic of uncertainty in ice accretion and cargo hold fire problems. The work done in this arena falls into one of a few categories: describing/modeling sources of uncertainty, developing and/or implementing methods for quantifying uncertainty, and analyzing the relative contributions to variance in a particular output quantity of interest. For completeness, we will address all three of these categories in this thesis.

1.1 Motivation and Goals

This work is motivated by the observation that both airfoil ice accretion and airplane cargo hold fires are fundamentally uncertain problems, which makes certification for safe flight challenging. Both of these safety concerns involve a significant amount of input process uncertainty, and the statistical effects of this uncertainty on important safety/performance metrics has not heretofore been thoroughly studied.

The goal of this work is to (1) show how input stochastic processes can be efficiently modeled, and (2) investigate the statistical effects of this uncertainty on important output quantities of interest. In the icing problem, we will investigate how aerodynamic performance metrics (e.g., lift) are affected statistically by uncertainty in the ice shape or in underlying physical conditions. In the cargo hold fire problem,

we will show how boundary condition uncertainty (e.g., position/heat flux of the fire source) can affect measures of fire detection (e.g., ceiling temperature distribution).

1.2 Approach

The approach we follow in this work is one which combines a number of techniques from the uncertainty quantification, low-dimensional modeling, and computational modeling communities. The breadth of techniques employed is needed to address the full scope of the icing/fire problems.

1.3 Contributions

Here is some text for the contributions introduction section.

Chapter 2

Related Work

Everyone needs a chapter about related work, so here is a placeholder.

2.1 Tables

Tables are also quite important. Any table that can fit entirely on one page can be a floating table. If a table is longer and will span multiple pages, a long table can be inserted in-line with the text. This is demonstrated in Table 3.1, and explained in Appendix A.

Tables that fit on one page use normal floating figures. Keep the 'p' placement option (in addition to 'h' and 't') so that if the float cannot fit in-line with the document text, it can be on a separate page by itself immediately after it is placed. Without the 'p' option, the float may get pushed to the end of the chapter, along with all other floats in the chapter that follow it.

Table 2.1 lists the various options for publishing your dissertation, with costs, as of 2010. You will have to bring a check for the appropriate amount, made out to “Princeton University Library”, when you submit your bound dissertation copies to Mudd Library, along with the appropriate forms and the electronic copy of your dissertation burned to a CD (not a DVD) as a single PDF file.

Traditional publishing is cheaper initially and lets you earn royalties if the publisher sells many copies of your dissertation. However, most of us won't have a best-seller dissertation and most likely won't earn royalties anyway. Instead, by choosing open access publishing, your dissertation will be available online for free to anyone who is interested. I strongly advocate for open access, to maximize the impact of your research.

Your dissertation is protected by copyright regardless of whether or not you have the copyright registered. However, registration establishes a public record of your copyright claim. ProQuest will submit the copyright registration for an extra fee (about \$55). Alternatively, you can register it yourself at the Copyright Office's website for only \$35: <http://www.copyright.gov/eco/>.

Table 2.1: Thesis publishing options, as of May 2010.

Publishing Method	Publishing Fee	Diploma Fee	Copyright Registration Fee	Total
Traditional Publishing				
Traditional without copy-right registration	65	15	–	80
Traditional with copy-right registration	65	15	55	135
Open Access				
Open access without copyright registration	160	15	–	175
Open access with copy-right registration	160	15	55	230

2.2 Figures

Everyone needs floating figures in their dissertation.

As shown in Figure 2.1, the Mudd Library dissertation requirements specify additional options for formatting the title page. For example, if your thesis has multiple volumes, or to indicate the proper formatting for a master's thesis.

Appendix B

TITLE OF DOCTORAL DISSERTATION [OR MASTER'S THESIS]

Volume (if more than one bound volume)

Legal Name of Author

A DISSERTATION [OR THESIS]
PRESENTED TO THE FACULTY
OF PRINCETON UNIVERSITY
IN CANDIDACY FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY [OR MASTER OF ARTS]

RECOMMENDED FOR ACCEPTANCE
BY THE DEPARTMENT OF [OR PROGRAM IN]
[NAME OF DEPARTMENT OR PROGRAM]
[Adviser: John Doe]

Month* Year

*(The month must be the one when the degree will be granted by the Board of Trustees.
Usually, the only acceptable months are January, April, June, September and November)

Figure 2.1: Sample title page layout

Chapter 3

Usage

To start, in your main .tex file, use this class as your main documentclass instead of ‘report’ or ‘book’. For example:

```
\documentclass[12pt,lot,lof]{puthesis}
```

In this example, we setup our document to use the PU Thesis style, with 12pt font for body text, and to include a List of Tables and List of Figures in the front matter. You could instead set an 11 point or 10 point font by changing the first option. You can also add ‘los’ to include a list of symbols.

To use single spacing, add the option ‘singlespace’. This is a special option for the `puthesis` documentclass, which sets single spacing for both the front matter and for the document itself. Additional parameters should be set in your main .tex file, and are described in detail in Section 3.1.

The template itself declares two other options, to be set immediately after the `documentclass` command. First is ‘printmode’, declared with the command:

```
\newcommand{\printmode}{}{}%
```

This command, used later in the thesis.tex file, turns off the `hyperref` package and all internal links in the PDF file. This removes any colored links and highlighting that

would not be appropriate in a printed and bound thesis. Instead the `url` package is loaded, so that

`url` commands in your document will continue to work and `urls` will break properly across multiple lines.

When ‘`printmode`’ is not specified, the `hyperref` package is included. It creates colored links for citations, footnotes, and internal references, which can be used to navigate the PDF document more easily. It also adds bookmarks to the PDF file, mirroring the table of contents. By default, it is set to use colored links. For the PDF file that you will submit electronically to ProQuest, this may not be desirable since some copies may be printed, while others will be used electronically. Thus another option, ‘`proquestmode`’, is defined that keeps `hyperref` but disables colored links:

```
\newcommand{\proquestmode}{}{}

```

This mode has no effect when used in combination with ‘`printmode`’.

3.1 Options

In this section, we describe the options you can set when using this thesis class.

Table 3.1: List of options for the `puthesis` document class and template

Option	Description
12pt	Specify the font size for body text as a parameter to <code>documentclass</code> . The Mudd Library requirements state that 12pt is preferred for serif fonts (e.g., Times New Roman) and 10pt for sans-serif fonts (e.g., Arial).
letterpaper	If your document is coming out in <code>a4paper</code> , your LaTeX defaults may be wrong. Set this option as a parameter to <code>documentclass</code> to have the correct 8.5”x11” paper size.
lot	Set this option as a parameter to <code>documentclass</code> to insert a List of Tables after the Table of Contents.

(Continued on next page)

Table 3.1: (continued)

Option	Description
lof	Set this option as a parameter to <code>documentclass</code> to insert a List of Figures after the Table of Contents and the List of Figures.
los	Set this option as a parameter to <code>documentclass</code> to insert a List of Symbols after the Table of Contents and the other lists.
singlespace	Set this option as a parameter to <code>documentclass</code> to single space your document. Double spacing is the default otherwise, and is required for the electronic copy you submit to ProQuest. Single spacing is permitted for the printed and bound copies for Mudd Library.
draft	Set this option as a parameter to <code>documentclass</code> to have L ^A T _E Xmark sections of your document that have formatting errors (e.g., overfull hboxes).
<code>\newcommand {\printmode}{}{}</code>	Insert this command after the <code>documentclass</code> command to turn off the hyperref package to produce a PDF suitable for printing.
<code>\newcommand {\proquestmode}{}{}</code>	Insert this command after the <code>documentclass</code> command to turn off the ‘colorlinks’ option to the hyperref package. Links in the pdf document will then be outlined in color instead of having the text itself be colored. This is more suitable when the PDF may be viewed online or printed by the reader.
<code>\makefrontmatter</code>	Insert this command after the <code>\begin{document}</code> command, but before including your chapters to insert the Table of Contents and other front matter.
<code>\title</code>	Set the title of your dissertation. Used on the title page and in the PDF properties.
<code>\submitted</code>	Set the submission date of your dissertation. Used on the title page. This should be the month and year when your degree will be conferred, generally only January, April, June, September, or November. Check the Mudd Library rules for the appropriate deadlines.
<code>\copyrightyear</code>	Set the submission year of your dissertation. Used on the copyright page.
<code>\author</code>	Your full name. Used on the title page, copyright page, and the PDF properties.

(Continued on next page)

Table 3.1: (continued)

Option	Description
<code>\adviser</code>	Your adviser’s full name. Used on the title page.
<code>\departmentprefix</code>	The wording that precedes your department or program name. Used on the title page. The default is “Department of”, since most people list their department and can leave this out (e.g., Department of Electrical Engineering), however if yours is a program, set <code>\departmentprefix{Programin}</code>
<code>\department</code>	The name of your department or program. Used on the title page.
<code>\renewcommand</code> <code>{\maketitlepage}{}{}</code>	Disable the insertion of the title page in the front matter. This is useful for early drafts of your dissertation.
<code>\renewcommand*</code> <code>{\makecopyrightpage}{}{}</code>	Disable the insertion of the copyright page in the front matter. This is useful for early drafts of your dissertation.
<code>\renewcommand*</code> <code>{\makeabstract}{}{}</code>	Disable the insertion of the abstract in the front matter. This is useful for early drafts of your dissertation.

I’ve seen other people print their dissertations using `\pagestyle{headings}`, which places running headings on the top of each page with the chapter number, chapter name, and page number. This documentclass is not currently compatible with this option – the margins are setup to be correct with page numbers in the footer, placing them 3/4” from the edge of the paper, as required. If you wish to use headings, you will need to adjust the margins accordingly.

Chapter 4

Conclusion

In this work, we explain how to use the puthesis.cls class file and the accompanying template.

4.1 Future Work

Future work should include options in the template for a masters thesis or an undergraduate senior thesis. It should also support running headings in the headers using the ‘headings’ pagestyle. The print mode and proquest mode included in the template might also be candidates to include in the class itself.

Appendix A

Implementation Details

Appendices are just chapters, included after the `\appendix` command.

A.1 Switching Formats

When switching `printmode` on and off (see Section 3.1), you may need to delete the output `.aux` files to get the document code to compile correctly. This is because the `hyperref` package is switched off for `printmode`, but this package inserts extra tags into the contents lines in the auxiliary files for PDF links, and these can cause errors when the package is not used.

A.2 Long Tables

Long tables span multiple pages. By default they are treated like body text, but we want them to be single spaced all the time. The class therefore defines a new command, `\tablespacing`, that is placed before a long table to switch to single spacing when the rest of the document is in double spacing mode. Another command, `\bodyspacing`, is placed after the long table to switch back to double spacing. Normal

tables using `tabular` automatically use single spacing and do not require the extra commands.

When the documentclass is defined with the ‘`singlespace`’ option, these commands are automatically adjusted to stay in single spacing after the long table.

Make sure there is always at least one blank line after the `\bodyspacing` command before the end of the file.

Some times long tables do not format correctly on the first pass. If the column widths are wrong, try running the \LaTeX compiler one or two extra times to allow it to better calculate the column widths.

If you want your long table to break pages at a specific point, you can insert the command `\pagebreak[4]`, to tell \LaTeX that it really should put a page break there. `\pagebreak[2]` gives it a hint that this is a good place for a page break, if needed. If there’s a row that really should not be broken across a page, use `*`, which will usually prevent a pagebreak.

A.3 Booktabs

The booktabs package is included to print nicer tables. See the package documentation for more details and motivation. Generally, all vertical lines are removed from the tables for a better visual appearance (so don’t put them in), and better spacing and line thicknesses are used for the horizontal rules. The rules are defined as `\toprule` at the top of the table, `\midrule` in between the heading and the body of the table (or between sections of the table), and `\bottomrule` at the end of the table. `\cmidrule` can be used with the appropriate options to have a rule that spans only certain columns of the table.

A.4 Bibliography and Footnotes

The bibliography and any footnotes can also be single spaced, even for the electronic copy. The template is already setup to do this.

Bibliography entries go in the .bib file. As usual, be sure to compile the \LaTeX code, then run BibTeX, and then run \LaTeX again.

To cite websites and other electronically accessed materials, you can use the ‘@electronic’ type of BibTeX entry, and use the ‘howpublished’ field to include the URL of the source material.

The formatting of bibliography entries will be done automatically. Usually the titles are changed to have only the first word capitalized. If you’d prefer to have your original formatting preserved, place the title in an extra set of curly braces, i.e., “title = {{My title has an AcroNyM that should stay unchanged}},”.

A.5 Figures and Tables

The captions of figures and tables take an optional parameter in square brackets, specifying the caption text to be used in the Table of Contents. The regular caption in curly braces is used for the table itself.

Generally captions for tables are placed above the table, while captions for figures are placed below the figure.

Appendix B

Printing and Binding

B.1 Printing

For the library copies of your dissertation, you must use archival quality printing and binding. This means acid-free paper, containing at least 25% cotton fiber. Triangle Repocenter on Nassau Street in Princeton offers both 25% cotton paper and 100% cotton paper. Most people choose the 25% cotton paper, and this is generally recommended by the binders. The 100% copy paper is somewhat thicker and the extra expense is unnecessary.

Triangle offers online submission of your printing and binding order at: <http://triangleprinceton.com/collegiatebinding/thesis/>. If you request binding from them, they will deliver the paper copies to Smith-Shattuck Bookbinding for you and allow you to pick up the completed copies at their store on Nassau Street. The whole process takes 2-3 business days, but check with them in advance during the busy thesis-printing season in April and May.

Currently, your printed and bound dissertation copies can be single spaced. Only the electronic copy submitted to ProQuest must be double spaced. All copies must be printed single-sided, with specific margins.

B.2 Binding

An archival-quality sewn binding is required for the library copies of your dissertation. Smith-Shattuck Bookbinding is highly recommended, and is used by most students. Triangle Repocenter will send your copies there for you, greatly simplifying the process, but you can call Smith-Shattuck with special requests.

The “library standard” sewn binding is sufficient for the copies to be sent to Mudd Library. It uses a black buckram cloth cover, which is the most popular option. For extra copies for yourself and your family members, you can choose “buckram roundback binding”, which adds decorative lines on the spine, and printing of the title and author on the front cover. For a small additional fee, you can include the Princeton University shield on the front cover and a ribbon bookmark. Leather covers are also available. See Smith-Shattuck’s website for more details at: <http://www.thesisbookbinding.com/>.

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