Xoptfoil Version 1.11.1 User Guide

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Contents

1 Installing

1.1 Linux

Precompiled binaries are not provided for Linux, because it is generally very easy to get the software required to compile it, and a build script is provided for convenience. CMake version 2.8.8 or later is required, as are gcc, g++, and gfortran. Your distribution should have packages for all of these, so locate and install them first through the package manager.

Once the requirements are installed, all that is necessary is to run the build script. Navigate to the top-level Xoptfoil directory and open a terminal window there. Then, run the build script using the following command:

```
sh build_linux.sh
```

or, as long as you have set executable permissions on the script, you can just use:

```
./build_linux.sh
```

If all goes well, Xoptfoil and its related tools will be installed in linux/bin under the top-level Xoptfoil directory. If desired, it is possible to change this location by changing the INSTALLDIR variable in the build script.

You may want to edit your PATH environment variable so that Xoptfoil and its related tools can be run from any directory. This is done by adding a line to your shell startup script, normally $HOME/.bashrc, like the following:

```
export PATH=/path/to/Xoptfoil/linux/bin:$PATH
```

where the string above is changed to the actual location where Xoptfoil is installed. A different approach is to install Xoptfoil in a system location, which can be accomplished most easily by simply removing the line '-DCMAKE_INSTALL_PREFIX:PATH="$INSTALLDIR" \' in the build script. The build script will need to be run with root privileges with this approach. Executables will then be installed in /usr/local/bin, which should already be in the PATH.

1.2 Windows

The Windows release includes precompiled binaries of Xoptfoil and its related tools. There are both 64-bit and 32-bit binaries. Both should work on a 64-bit operating system, but only the 32-bit binaries will work on a 32-bit operating system. The release also includes some required libraries so that the user does not have to install compilers just to run Xoptfoil. As of Xoptfoil 1.11.0, parallel processing is supported in the precompiled versions; it is not necessary to compile the code manually to benefit from this feature.

Currently, the Windows release does not have an official installer; all that is needed is to unzip the release package and place it somewhere convenient. The executables and runtime libraries are located in the bin directory. For convenience, it is recommended to add this directory to the PATH so that Xoptfoil can be executed from other locations. If you don't do this step, you will need to always run it from the bin directory where the executables are located or specify the full path when referencing the executables. To add the Xoptfoil bin directory to your path, on Windows 10:

1. Type "environment" in the search box in the task bar.

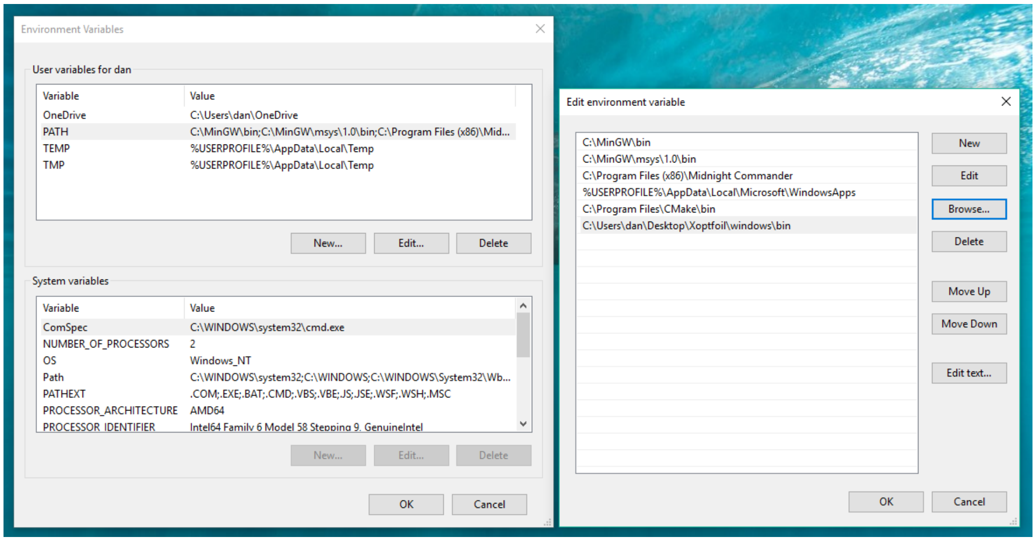


Figure 1: Adding Xoptfoil to the PATH environment variable in Windows.

2. Select "Edit environment variables for your account."
3. In the top box, labeled "Environment variables for <user>," select PATH and then click EDIT.
4. In the window that appears, add a new entry and then type the location or browse to the Xoptfoil bin directory. Make sure you do not overwrite any existing entries.
5. Click OK in both windows to save the settings.

The two windows should look something like Fig. 1. On older versions of Windows, the process is similar, but you may need to navigate to the correct area of the Control Panel to find the environment variable settings, e.g. Control Panel → System → Advanced → Environment variables. If you are having trouble finding it, do an internet search for how to set the PATH environment variable on your version of Windows.

1.2.1 Optional: compiling

It is not necessary to compile Xoptfoil on Windows, but you are free to do so if desired (or if you want to make changes to the code). There are a couple prerequesites for compiling on Windows:

- CMake version 2.8.8 or later, and
- MinGW32 or MinGW64 including the gcc, g++, and gfortran compilers.

To install CMake, just download and run the installer from the website: `https://cmake.org/download/`. Installing MinGW32 is a little bit more complicated. The main page for MinGW is `mingw.org`. The installation instructions are at `http://mingw.org/wiki/Getting_Started`. Follow the instructions under the section "Graphical User Interface Installer" first. This process will install the MinGW installation manager, which is a graphical tool used to download and install the MinGW compilers. In addition to the compilers, you should also install mingw32-make and any pthreads packages (on MinGW32, these are called mingw32-pthreads-w32). The precompiled binaries have been built with GCC version 6.3.0 on MinGW32 and 5.4.0 on MinGW64, so these versions are known to work. MinGW64 can be downloaded at `https://sourceforge.net/projects/mingw-w64/files/mingw-w64/`. However, if your operating system in 64-bit, MinGW32 will also work fine; you do not need to use MinGW64.

At this point, everything you need to compile Xoptfoil should be installed. A build script is provided in the top-level Xoptfoil directory. Though you can run it by double-clicking, it is recommended to run it from the command line so that the output is visible in case anything goes wrong. Open a command prompt in that directory browsing there in Windows explorer, Shift + right-clicking, and selecting "Open command window here." Then, run the build script by entering the following command:

```
build_windows.bat
```

If all goes well, Xoptfoil and its related tools will be installed in windows\bin under the top-level directory.

1.3 Mac OSX

To install Xoptfoil on Max OSX, you will need to compile it. (Unfortunately, I don't have a Mac available to create binaries and do testing.) As with the other platforms, CMake and a compiler suite are required. CMake is available as a dmg file from the official website: `https://cmake.org/download/`. The GNU compilers are recommended (gcc, g++, and gfortran), which are available for Mac OSX at `http://gcc.gnu.org/wiki/GFortranBinaries#MacOS`. Because Mac OSX is a Unix-like system, the build script for Linux should work for Mac OSX as well. Therefore, after installing CMake and the compilers, you can refer to the Linux compiling instructions in Section 1.1 for the rest of the process.

2 Running Xoptfoil

Xoptfoil is a command-line program. While it is possible to run it by double-clicking on the executable file, it is better to run it from the command line. (If you double-click to run it and there is an error, the window will disappear and you won't be able to read the error message.) Open a terminal ("command prompt" in Windows) and navigate to the directory where you intend to run Xoptfoil. (In the Windows file explorer, you can Shift + right click and select "Open command window here." Many Linux file browsers have a similar option.)

Note: these instructions assume that you have added the Xoptfoil bin directory where binaries are located to the PATH environment variable as described in Section 1. To run Xoptfoil, simply type the following command:

```
xoptfoil
```

This command will run Xoptfoil in the current working directory. Xoptfoil uses an input file called 'inputs.txt,' which must also be in the working directory. If the input file is not in the working directory where Xoptfoil is run, the program will notify you that it can't find the file and then stop. It is also possible to use an input file with a different name; see Section 2.1 for instructions.

By default, Xoptfoil writes output files with the prefix 'optfoil' (the final optimized airfoil is called 'optfoil.dat'). However, it is also possible to change the output prefix, as described in Section 2.1.

2.1 Command line options

Xoptfoil accepts the following command-line options:

- -i {input file}
  - Specify an input file other than 'inputs.txt.' Replace {input file} with the name (if in the working directory) or full path to the input file.
- -o {output prefix}
  - Specify an output prefix other than 'optfoil.' Replace {output prefix} with the desired string.
- `-h, --help`
  - Display usage information and exit.
- `-v, --version`
  - Display Xoptfoil version and license information and exit.

By way of example, if you wanted to use an input file called 'test.txt' and have output files written with the prefix 'my_airfoil,' you would invoke Xoptfoil with the following command:

```
xoptfoil -i test.txt -o my_airfoil
```

3 Controlling an ongoing optimization

When Xoptfoil starts an begins an optimization, it creates an empty file called "run_control." The user can enter commands in this file to control an ongoing optimization. The currently available commands are:

- **stop**: Write restart data and stop the optimization at the end of the current iteration. Also writes a stop_monitoring command, which is described in the next point.
- **stop_monitoring**: In xoptfoil_visualizer, stop monitoring the current optimization and return to the main menu. See Section 7 for more information.

4 Input file

Xoptfoil reads a Fortran namelist input file called 'inputs.txt' (unless a different name is specified as a CLO, as described above). This file stores conditions for optimization, such as the optimization type, parameterization settings, aerodynamic operating conditions and constraints, the seed airfoil, Xfoil options, etc. There are a number of categories of inputs, each of which is stored in a separate namelist. A Fortran namelist is formatted as follows:

```
&namelist_title
  input1 = value1          %Comments are preceeded by a percent sign
  input2 = value2
  textinput1 = 'string1'
  etc.
/
```

Each namelist begins with a '&' character followed immediately by the title, and it ends with a '/' character. Variables for each namelist are then listed with their respective values. To change an input, simply change the value to the right of the '=' sign. Note that text-based inputs (for example, the name of the seed airfoil file) need to be surrounded by single or double quotes. The inputs for each of the Xoptfoil namelists, stored in 'inputs.txt,' are explained in the following sections. A sample input file called 'all_inputs.txt' is included with Xoptfoil. This file contains all possible inputs with comments. Many of the inputs are not required, however, and default values will be used if they are absent. Any absent required inputs will result in an error when Xoptfoil is run.

4.1 optimization_options namelist

In this namelist, high-level optimization and parameterization parameters are set. Each of the inputs is described in the list below.

1. **search_type**: May be 'global', 'local', or 'global_and_local'. A global search is an expensive approach like particle swarm or a genetic algorithm which includes many potential designs to attempt to converge on the global best solution. A local search is one that investigates the design space in the vicinity of the initial design (the seed airfoil), looking for improvements. A local search is much faster than a global search, but it also usually does not find as good a final solution. If this input is set to 'global_and_local', a global search is first performed, followed by a local search.

2. **global_search**: Optimization algorithm for the global search. Either 'particle_swarm' or 'genetic_algorithm'.

3. **local_search**: Optimization algorithm for the local search. Currently, the only available option is 'simplex'.

4. **seed_airfoil**: Defines how to set the seed airfoil. Available options are (1) 'from_file', whereby the seed airfoil is read from a file, or (2) 'naca', where a NACA seed airfoil is generated by Xoptfoil. If 'naca' is selected, the parameters for generating the airfoil must be set in the naca_airfoil namelist.

5. **airfoil_file**: File name for the seed airfoil, which is used if seed_airfoil = 'from_file'. The file must be formatted in Xfoil format; it may have a label on the first line (though it does not need to) and then the coordinates must be arranged in two columns for x and y, forming a closed loop beginning and ending at the trailing edge. There should be no blank lines, and you should also not include the number of points or any other information besides a header and then the data. If the file is not in the working directory, you must include the full or relative path.

6. **shape_functions**: Identifier for the shape functions used to parameterize airfoils in the optimization. This may be 'naca' or 'hicks-henne'. A user-defined number of these shape functions are added to the top and bottom surfaces of the seed airfoil to create new shapes. 'naca' functions are a family of functions which, when combined in a weighted sum, can reproduce many of the NACA airfoils, including four-digit and transonic airfoils. 'hicks-henne' are a more general class of functions which place a "bump" of variable width and location on the airfoil surface. Each Hicks-Henne shape function, therefore, has a strength and also a width and location, whereas each NACA function only has a strength.

7. **min_bump_width**: Minimum width of Hicks-Henne bump function. Too small a value is more likely to result in a final design with small "bumps" present. Default value is 0.1 (10% chord).

8. **nfunctions_top**: The number of shape functions used to parameterize the top surface of the airfoil. Note that if you are using Hicks-Henne functions, 1/3 the number of shape functions will give the same number of design variables and a similar range of possible shapes as the NACA functions. For example, you may use 4 Hicks-Henne functions instead of 12 NACA functions to have the same number of total design variables.

9. **nfunctions_bot**: The number of shape functions used to parameterize the bottom surface of the airfoil. See the note on nfunction_top regarding differences between NACA and Hicks-Henne functions.

10. **initial_perturb**: The maximum strength of the shape functions used when generating initial designs.

11. **restart**: Whether or not to restart a prior optimization that terminated early – .true. or .false. If enabled, files with the pattern restart_* from the previous run must be present, and most inputs should be kept the same. See Section 6 for more information.

12. **restart_write_freq**: How often to write restart files, in terms of number of iterations.

13. **write_designs**: Whether to write airfoil coordinates and polars to files during the optimization. See Section 5 for more information on the output files generated.

4.2 operating_conditions namelist

This namelist specifies aerodynamic operating conditions over which to optimize the airfoil. These are the operating points at which each potential design will be evaluated, including angle of attack or lift coefficient, Reynolds number, Mach number, and relative weighting of each operating point.

1. **noppoint**: The total number of operating points at which to evaluate potential designs. A maximum of 30 is allowed. Including more operating points makes the final design more robust, but there is probably also a point of diminishing returns. With only one or two operating points, the final airfoil will probably perform quite well at those conditions but do poorly elsewhere. Including more operating points is more expensive, however, because Xfoil must be run for each airfoil at each operating point. With many operating points, it is also more likely for Xfoil to not converge at one of them, which will result in the optimizer essentially throwing out that design. Typically, 5 - 10 operating points spanning the range of needed conditions is a good number.

2. **use_flap**: Whether flap deflections will be applied in the optimization.

3. **x_flap**: Flap hinge point in x (between 0 and 1). Only used if use_flap is enabled.

4. **y_flap_spec**: Method of specifying vertical hinge location. Either 'y/c' (vertical location normalized by chord length) or 'y/t' (vertical location normalized by local thickness at x_flap). The default is 'y/c'. Only used if use_flap is enabled.

5. **y_flap**: Flap hinge point in y. Only used if use_flap is enabled. If y_flap_spec is 'y/c', y_flap refers to the vertical location of the hinge normalized by the chord length. If instead y_flap_spec is 'y/t', the position is normalized by the local thickness at x_flap. In the latter case, for example, -1.0 places the hinge at the lower surface, and 1.0 places it at the upper surface.

6. **op_mode(n)** (where n is an integer ranging from 1 to noppoint): Tells Xfoil whether the angle of attack or lift coefficient is being specified for this operating point. May be 'spec-al' for specified angle of attack or 'spec-cl' for specified lift coefficient. 'spec-cl' is usually more useful, because generally the lift coefficient is known as a function of the aircraft weight and flight speed during design.

7. **op_point(n)** (where n is an integer ranging from 1 to noppoint): Specifies either the angle of attack (in degrees) or the lift coefficient for this operating point, depending on whether op_mode is 'spec-al' or 'spec-cl' for this operating point. Note that Xfoil calculations are not accurate above stall, so do not specify too large a lift coefficient or angle of attack.

8. **optimization_type(n)**: (where n is an integer ranging from 1 to noppoint): Specifies the optimization objective for this operating point. Current options include 'min-drag' (to minimize drag), 'max-glide' (to maximize glide slope), 'min-sink' (to minimize sink rate), 'max-lift' (to maximize lift at a specified angle of attack), 'max-xtr' (to move the turbulent transition location as far towards the trailing edge as possible), or 'max-lift-slope' (to maximize the lift curve slope at operating point n).

9. **reynolds(n)** (where n is an integer ranging from 1 to noppoint): Specifies the Reynolds number based on chord for this operating point.

10. **mach(n)** (where n is an integer ranging from 1 to noppoint): Specifies the Mach number for this operating point. Note that Xfoil calculations are not accurate at or above the transonic regime, so do not specify too high a Mach number.

11. **flap_selection(n)** (where n is an integer ranging from 1 to noppoint): Options are 'specify' or 'optimize'. In the former case, the input value of flap_degrees will be used at this operating point for *all* designs considered by the optimizer. In the latter case, the optimizer will consider the flap deflection as a design variable and optimize it at this operating point. The value of flap_degrees will then be used only for the seed airfoil to establish the reference seed airfoil performance.

12. **flap_degrees(n)** (where n is an integer ranging from 1 to noppoint): Specifies the flap deflection for this operating point, in degrees, with a positive deflection being in the downward direction. Only used if use_flap is enabled. The optimized flap deflection is subject to the constraints max_flap_degrees and min_flap_degrees.

13. **weighting(n)** (where n is an integer ranging from 1 to noppoint): Specifies the weighting for this operating point. Operating points with a higher weighting are given more importance by the optimizer. Note that the weightings are automatically normalized by the optimizer so that they add up to 1.

14. **ncrit_pt(n)** (where n is an integer ranging from 1 to noppoint): Specifies ncrit for this operating point. If not specified, the ncrit value from the xfoil_run_options namelist will be used.

4.3 constraints namelist

Specifies aerodynamic and geometric constraints for the optimization. Constraints are implemented in the optimizer by assigning a large penalty value whenever a constraint is violated.

1. **min_thickness**: The minimum allowable thickness of designs, as a fraction of the chord (for example, 0.08 means 8% thickness). A minimum allowable thickness is usually required for structural reasons. If you don't want to impose this constraint, just set it to 0.

2. **max_thickness**: The maximum allowable thickness of designs, as a fraction of the chord (for example, 0.08 means 8% thickness). This can be used to set an upper bound on max airfoil thickness. If you don't want to use this constraint, just set it to a very large number like 1000 (or just don't specify a max_thickness, as 1000 is the default value).

3. **min_camber**: The minimum allowable camber of designs, as a fraction of the chord (for example, 0.02 means 2% camber). If you don't want to impose this constraint, set it to some large negative value (the default is -0.10).

4. **max_camber**: The maximum allowable camber of designs, as a fraction of the chord (for example, 0.02 means 2% camber). If you don't want to impose this constraint, set it to some large positive value (the default is 0.10).

5. **moment_constraint_type(n)** (where n is an integer ranging from 1 to noppoint): How to implement the pitching moment constraint for the specified operating point. Either 'none', 'specify', or 'use_seed'. If 'none', then no pitching moment constraint is applied at this operating point. If 'specify', then the user specifies the minimum allowable moment using the min_moment constraint. If 'use_seed', then the pitching moment from the seed airfoil at this operating point will be taken as the minimum allowable.

6. **min_moment(n)** (where n is an integer ranging from 1 to noppoint): The minimum allowable pitching moment coefficient at the specified operating point. A larger negative pitching moment will require a larger tail. For flying-wing airfoils, this is usually set to 0. This input is only used if moment_constraint_type = 'specify'.

7. **max_flap_degrees**: Maximum flap angle, in degrees, for 'optimize' flap selection type in operating_conditions, where positive corresponds to a downward deflection.

8. **min_flap_degrees**: Minimum flap angle, in degrees, for 'optimize' flap selection type in operating_conditions, where positive corresponds to a downward deflection.

9. **min_te_angle**: The minimum trailing edge wedge angle, in degrees. Without this constraint, the optimizer may converge on airfoils with a very thin cusped aft section, which is challenging to build and presents structural problems. If you don't want to impose this constraint, just set it to 0.

10. **check_curvature**: Whether to check the curvature for applying a curvature reversals constraint. If you don't want to apply a curvature reversals constraint, set this to .false., because checking the curvature adds computational cost. Set this to .true. if you wish to specify a constraint on the number of curvature reversals.

11. **max_curv_reverse_top**: Maximum allowed number of curvature reversals on the top surface within the specified curvature threshold. If you wish to use this constraint, you

must enable check_curvature. The default is 0. Increasing it may improve the predicted performance but also may produce more wavy designs.

12. **max_curv_reverse_bot**: Maximum allowed number of curvature reversals on the bottom surface within the specified curvature threshold. If you wish to use this constraint, you must enable check_curvature. The default is 1, so a single curvature reversal is allowed on the bottom surface. Increasing it may improve the predicted performance but also may produce more wavy designs.

13. **curv_threshold**: Curvature thresshold for detecting reversals. The local curvature can be thought of as 1/r, where r is the local radius. So, for instance, a curvature threshold of 0.2 means that any reversals with a radius greater than 5.0 will be ignored. If you make this value too small, it may be very hard for the optimizer to come up with feasible designs, so you may need to increase feasible_init_attempts. The default is 0.1.

14. **symmetrical** (.true. or .false.): Whether to only generate symmetrical airfoils. If true, only the top surface of the seed airfoil will be modified, and the bottom surface will be replaced by a mirrored version of the top surface. This option is useful if you want to ensure that the final optimized airfoil is symmetrical. The seed airfoil does not need to be symmetrical to use this option (but note that Xoptfoil will actually be using a symmetrical version of the seed airfoil instead of the actual one).

15. **naddthickconst**: Number of additional thickness constraints to specify. The max allowed is 10.

16. **addthick_x(n)** (where n is an integer ranging from 1 to naddthickconst): x/c location where additional thickness constraint n is applied.

17. **addthick_min(n)** (where n is an integer ranging from 1 to naddthickconst): The minimum thickness allowed at the location specified by addthick_x(n).

18. **addthick_max(n)** (where n is an integer ranging from 1 to naddthickconst): The maximum thickness allowed at the location specified by addthick_x(n).

4.4 naca_airfoil namelist

This namelist specifies options for generation of a NACA airfoil, which are used if seed_airfoil = 'naca' in the optimization_options namelist. NACA airfoil generation is provided by the naca456 code from `http://www.pdas.com`, which has been adapted for Xoptfoil. Instead of specifying a 4-, 5-, or 6-digit code with limited precision, most inputs are supplied as real numbers, which allows greater precision (e.g., you can create a 4-digit airfoil with 2.5% camber). However, be aware that some families are only intended to be used with specific ranges of these inputs, and setting a parameter too large or small may result in an unexpected shape. This mainly true of the 4M and 5 families. Therefore, the user should do some research first to see what ranges are allowed.

1. **family**: NACA airfoil family. Options are '4', '4M', '5', '63', '64', '65', '66', '67', '63A', '64A', or '65A'.

2. **maxt**: Max thickness as a fraction of chord. For example, for a 10%-thick airfoil, use maxt = 0.10.

3. **xmaxt**: Location of maxt as a fraction of chord. This input is only used for the 4M family.

4. **maxc**: Max camber as a fraction of chord. For example, for 2% camber, use maxc = 0.02. This input is only used for the 4 and 4M families (others use design_cl instead to adjust the camber).

5. **xmaxc**: Location of maxc as a fraction of chord.

6. **design_cl**: Design lift coefficient. This input is only used for the 5, 6, and 6A families.

7. **a**: Extent of constant load for the 6 family. It is specified as a fraction of chord.

8. **leidx**: Leading edge index for the 4M family.

9. **reflexed** (.true. or .false.): Whether the mean camber line is reflexed. This input is only used for the 5 family.

4.5 initialization namelist

This namelist specifies options for initialization a population of designs for the global search methods (particle swarm and genetic algorithm).

1. **feasible_init** (.true. or .false.): If true, attempts to place initial designs in the feasible space. If an initial design violates constraints, a large penalty value will be added to the objective function. feasible_init will re-randomize designs that initially have too large an objective function value. This process increases the overall expense of the optimization but also improves the results because more of the initial designs will be good ones.

2. **feasible_limit**: The objective function value below which initial designs are considered feasible. Designs that violate constraints are added a penalty value on the order of 10^6, so the feasible limit should be large but at least an order of magnitude smaller than 10^6. The default value is 50,000.

3. **feasible_init_attempts**: Number of attempts to try to make an initial design feasible. The default is 1000. This number is usually sufficient to get most or all of the designs in the feasible space. However, if many of the designs cannot be made feasible within 1000 attempts, you should increase the number. (This may happen if very tight geometric constraints are applied.)

4.6 particle_swarm_options namelist

This namelist specifies options for particle swarm optimization, which are used if search_type = 'global' or search_type = 'global_and_local' and global_search = 'particle_swarm'.

1. **pso_pop**: Number of particles. These are randomly initialized throughout the design space and then use swarming behavior to converge on the global optimimum. Search cost increases linearly with population size. Usually, around 40 or 50 particles seem to work well.

2. **pso_tol**: Tolerance in max radius of particles before triggering a stop condition. When all particles are within this radius of the population center, the particle swarm optimization process will stop even if the max number of iterations has not been reached. The default value is 0.0001.

3. **pso_maxit**: Maximum number of iterations allowed before the particle swarm optimization is stopped. The default value is 700. Using the 'quick' convergence profile, the optimization will usually converge in less than 700 iterations. However, if you use the 'exhaustive' profile, it likely will not converge within the default 700 iterations, but the airfoil design will probably not improve much after that.

4. **pso_convergence_profile**: Either 'exhaustive' or 'quick'. This setting adjusts some parameters in the particle swarm algorithm which affect how quickly the optimization converges. The quick profile works well and converges quickly. The exhaustive profile usually is able to find a little bit better designs than the quick profile, but it also takes much longer to converge (e.g., 700 iterations instead of 150).

4.7 genetic_algorithm_options namelist

This namelist specifies options for genetic algorithm optimization, which are used if search_type = 'global' or search_type = 'global_and_local' and global_search = 'genetic_algorithm'.

1. **ga_pop**: Number of designs in the population. These are randomly initialized throughout the design space and then use reproduction and replacement mechanisms to converge on the global optimum. Search cost increases linearly with population size, as long as **parent_fraction** remains the same. Usually, around 80 to 100 particles seem to work well.

2. **ga_tol**: Tolerance in max radius of designs before triggering a stop condition. When all designs are within this radius of the population center, the genetic algorithm optimization process will stop even if the max number of iterations has not been reached. The default value is 0.0001. Note: not all designs are considered in the design radius computation. Only the best nparents designs, where nparents is the number of designs that reproduce during each iteration, are considered. This is because the worst designs are typically less likely to reproduce (unless **parents_selection_method** is 'random') and may take a long time to move towards the optimum.

3. **ga_maxit**: Maximum number of iterations allowed before the genetic algorithm optimization process is stopped. The default value is 700. It is likely that the optimization process will not converge within the default 700 iterations, but the airfoil design will probably not improve much after that.

4. **parents_selection_method**: Method of selecting parents during each iteration. Available options are 'roulette', 'tournament', or 'random'. The first two are usually best. The default is 'tournament'.

5. **parent_fraction**: Fraction of the total population that reproduces during each iteration. The default is 0.5.

6. **roulette_selection_pressure**: Factor to increase the likelihood that the best designs are selected as parents when using the roulette parent selection method. The default value is 8.0.

7. **tournament_fraction**: Fraction of the total population that is randomly entered into the tournament for selecting parents designs, when **parents_selection_method** is 'tournament'. For example, if **tournament_fraction** is 0.1 and **ga_pop** is 100, then 10 designs

will be randomly selected, and the parent will be the best of these 10 designs. (This process is repeated for each parent that is selected.)

8. **crossover_range_factor**: If 0, crossover will result in design variables that are linear interpolations between parents. A value greater than 0 allows extrapolation to occur, which is recommended to ensure that the design space is adequately searched. The default value is 0.5, which means crossover can result in design variables that are 50% in excess of the difference in the parent values in either direction.

9. **mutant_probability**: The probability of mutation occurring in a given offspring. The default is 0.4, which means that there is a 40% probability that a given offspring design will be able to mutate.

10. **chromosome_mutation_rate**: For mutant designs, the probability that a given design variable (a.k.a. chromosome) will mutate. This should be small enough to not pollute the "genes" of good designs, but large enough that variation is introduced in the gene pool. The default is 0.01, which means that 1% of the design variables will mutate in child designs that are flagged for mutation.

11. **mutation_range_factor**: Maximum magnitude of mutation, as a fraction of the initially specified design variable range. For shape design variables, this range is defined by initial_perturb, and for flap design variables the range is the difference between the max and min flap angles. The default value is 0.2, or 20% of the range.

4.8 simplex_options namelist

This namelist specifies options for simplex optimization, which are used if search_type = 'local' or search_type = 'global_and_local' and local_search = 'simplex'.

1. **simplex_tol**: Tolerance in max radius of designs before triggering a stopping condition. When all designs are within this radius of the simplex center, the simplex optimization process will stop even if the max number of iterations has not been reached. The default value is 10^{-6}.

2. **simplex_maxit**: Maximum number of iterations allowed before the simplex optimization is stopped. Ensures that the simplex optimization does not go on for too long before the stopping condition is met.

4.9 xfoil_run_options namelist

This namelist specifies options that control how Xfoil calculations are run.

1. **ncrit**: Transition-triggering parameter. A higher number represents cleaner (less turbulent) freestream conditions. 9 is the default.

2. **xtript**: Top-surface trip location for turbulent transition. For free transition, set this to 1. 1 is the default.

3. **xtripb**: Bottom-surface trip location for turbulent transition. For free transition, set this to 1. 1 is the default.

4. **viscous_mode** (.true. or .false.): Whether to run Xfoil boundary layer calculations. The default is .true., which is recommended. If it is .false., the pressure drag is used as the drag coefficient, which isn't very meaningful for real designs.

5. **silent_mode** (.true. or .false.): If .true., suppresses Xfoil screen writes. This is desirable for optimization, because thousands of designs are tested and there is not time to read the Xfoil notifications anyway. For running Xfoil alone without optimizing, you may want to see the Xfoil screen writes. .true. is the default.

6. **bl_maxit**: Max number of iterations for viscous calculations. 100 is the default.

7. **vaccel**: Xfoil viscous convergence acceleration parameter. 0.01 is the default.

8. **fix_unconverged** (.true. or .false.): Whether to try to fix unconverged operating points by reinitializing the boundary layer at a different operating condition. .true. is the default. This will make the optimization a little more expensive, but it helps to prevent good designs from getting penalized by non-convergence.

9. **reinitialize** (.true. or .false.): Whether to reinitialize the boundary layer at each consecutive operating point. .true. is the default, which seems to result in a more robust optimization, but you may want to experiment with this.

4.10 xfoil_paneling_options namelist

This namelist controls how Xfoil smooths airfoil paneling before running aerodynamic calculations. The options are the same as the PPAR menu in Xfoil.

1. **npan**: Number of airfoil panels.

2. **cvpar**: Panel bunching parameter. Increasing this number will cause more panels to be bunched in regions of high curvature. 1.0 is the default.

3. **cterat**: Ratio of trailing-edge to leading-edge panel density. 0.15 is the default.

4. **ctrrat**: Ratio of regular panel density to refined-area panel density. 0.2 is the default.

5. **xsref1**: Left top side refinement limit. 1.0 is the default, which means there is no refined area on the top side.

6. **xsref2**: Right top side refinement limit. 1.0 is the default.

7. **xpref1**: Left bottom side refinement limit. 1.0 is the default, which means there is no refined area on the top side.

8. **xpref2**: Right bottom side refinement limit. 1.0 is the default.

4.11 matchfoil_options namelist

This namelist is used for testing new optimization algorithms and parameterization schemes. Instead of running an aerodynamic optimization (which is expensive), this namelist allows you to try to match the seed airfoil shape to another known airfoil shape, and Xfoil is never run. It's about a million times faster than aerodynamic optimization (rough estimate), which makes it good for testing things.

1. **match_foils** (.true. or .false.): If .true., the optimizer will try to match the seed airfoil shape to another known airfoil shape, and no aerodynamic calculations will be performed. .false. is the default.

2. **match_foil_file**: Text string specifying the file name of the airfoil which is to be matched by the optimizer. The coordinates must be given in Xfoil format, meaning the first line can be a label (but it doesn't have to be), and then the x and y coordinates must follow in two columns arranged in a single loop beginning and ending at the trailing edge. If the file is not in the working directory, you must include the relative path.

5 Output files

The following files are written out by the program. By default, {prefix} is "optfoil," unless otherwise specified with the -o command line option as described in Section 2.1.

1. **{prefix}.dat**: The coordinates of the final optimized design.

2. **{prefix}_performance_summary.dat**: Aerodynamic data for the final optimized design at the requested operating points.

3. **{prefix}_design_coordinates.dat**: Airfoil coordinates for each progressively better design found during the optimization. Only written if the option write_designs is set to .true. Each new design is identified under one of the "zone t=..." labels. You can plot these using xoptfoil_visualizer. See Section 7 for more information.

4. **{prefix}_design_polars.dat**: Airfoil polars (lift, drag, pitching moment coefficients, and transition locations) at the requested operating points for each progressively better design found during the optimization. Only written if the option write_designs is set to .true. Each new design is identified under one of the "zone t=..." labels. You can plot these using xoptfoil_visualizer. See Section 7 for more information.

5. **optimization_history.dat**: Convergence information from the optimizer, including the iteration, objective function value of the best design, percent improvement over the seed airfoil, and radius of the candidate designs. This information can be plotted using xoptfoil_visualizer; see Section 7 for more information.

6. **A number of files with the pattern restart_*_{prefix}**: Restart data written by Xoptfoil. These files are required to restart a prior optimization that was terminated early. More information is available in Section 6.

6 Restarting an optimization

Because Xoptfoil can take several hours to optimize an airfoil design, sometimes it is desirable to terminate an optimization early and pick up again later. Terminating an ongoing optimization may be done by entering the "stop" command in the run_control file. Xoptfoil can restart a prior optimization by reading restart files that are written periodically. The file restart_status_{prefix} saves the current optimization method being used, either global optimization (i.e., particle swarm) or local optimization (simplex). The file restart_pso_{prefix} contains data required by the particle swarm optimizer to restart a prior optimization. Similarly, the file restart_ga_{prefix} contains restart data for the genetic algorithm, and restart_simplex_{prefix} contains restart data for the simplex search. Each of these files must be present in the working directory when Xoptfoil is run in order to restart properly.

The two relevant inputs are **restart** and **restart_write_freq** in the optimization_options namelist. For a new optimization, **restart** should be set to .false., but it must be .true. to restart a prior optimization. **restart_write_freq** specifies how often restart data is written to files, in terms of iterations. Other than **restart**, the rest of the inputs should be the same when restarting an optimization. However, it is possible to also change any settings that do not affect the number of design variables or population of designs and still restart successfully. For example, Xfoil paneling and run options can be changed when restarting, but the number of operating points cannot.

7 Using xoptfoil_visualizer

A Python script called xoptfoil_visualizer.py is provided to plot and animate airfoil designs generated during the optimization process, either while the optimization is going on or afterwards. In order to use this tool, it is necessary to have Python with matplotlib and numpy installed. It has been tested with Python 2.7.x and Python 3.6.x, and matplotlib version 1.5.0 or higher is recommended. On Windows, the easiest way to achieve this is to install one of the free packaged Python distributions. The Anaconda Python distribution is recommended because it is easy to install and includes up-to-date versions of all the required packages. Anaconda can be downloaded here: `https://www.continuum.io/downloads`.

When installing Anaconda (or whichever Python distribution is chosen), be sure to check the option to add Python to your PATH. That way, Python can be run from the command prompt. If you are not using Anaconda and the option to modify the system path is not offered, you should manually add the appropriate directory with the python executable to your path, following a similar method to the one described in Section 1.2 where the Xoptfoil bin directory was added to the path.

If you are using Linux, it is likely that you already have Python installed on your system. However, matplotlib may not be installed by default; if so, install it from your distribution's software repository. Note that there may be different packages for matplotlib and numpy depending on whether you are using Python 2 or Python 3. Again, matplotlib version 1.5.0 or higher is recommended.

To use xoptfoil_visualizer, you must first start an optimization with write_designs set to .true. In the same directory, run xoptfoil_visualizer using the following command:

```
xoptfoil_visualizer.py
```

Note that xoptfoil_visualizer.py must be present in the directory where you try to run it, or it must be in your PATH environment variable as described in Section 1. xoptfoil_visualizer is menu based. When it is run, it first asks for the case name of the optimization. By default, this is 'optfoil,' but it will be different if you specified a different name as a command line argument to xoptfoil. (It is the prefix in front of the files {prefix}_design_coordinates.dat and {prefix}_design_polars.dat.) The prompt looks like this:

```
Enter the case name for the optimization (e.g., optfoil, which
is the default case name):
```

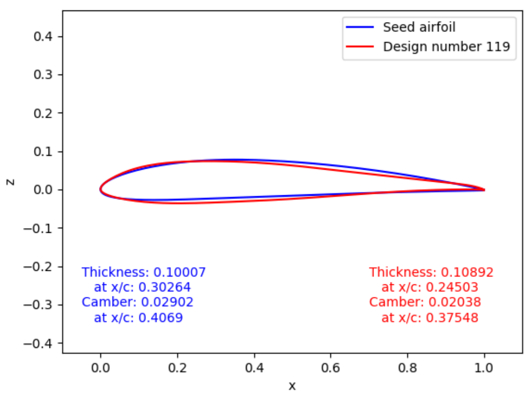
After specifying the case name, the tool will attempt to read the files. Provided they are present, the number of designs read from them will be printed to screen, and then the main menu will be shown. The following shows an example status notification for reading files with the case name 'optfoil' (the default), and below it the menu:

```
Reading airfoil coordinates from file optfoil_design_coordinates.dat...
Found 52 airfoil coordinates plus seed airfoil.
Reading airfoil polars from file optfoil_design_polars.dat...
Found 52 airfoil polars plus seed airfoil.

Options:
[0] Exit
[1] Plot a specific design
[2] Animate all designs
[3] Monitor an ongoing optimization
[4] Change plotting options

Enter a choice [0-4]:
```

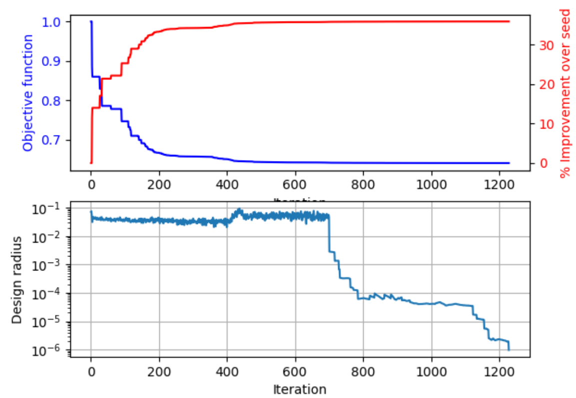
Option 1 will offer you the choice to plot any of the airfoils and polars that were generated during the optimization. It also will show the optimization history if that output file is present. Option 2 creates the same plots (except for the optimization history), but it loops through all the designs and displays them in sequence. Option 3 is similar to option 2, except that it is used to monitor the results of an ongoing optimization. When this option is selected, the output files from Xoptfoil are checked at a regular interval, and the plots are updated automatically when new data is available. Monitoring can be stopped by entering the command "stop_monitoring" (without quotes) on a new line in the run_control file, as described in Section 3. Plotting options can be changed by selecting option 4. Available plotting options include turning on/off various plot elements (such as the seed airfoil, the coordinate plot, and the polar plot), line colors, and the checking interval when monitoring an ongoing optimization. The plotting options menu also allows animation frames to be saved. When this option is enabled and option 2 is selected from the main menu, each frame of the animation will be saved to a PNG image file, which can later be combined together into a movie by a separate application such as ffmpeg. By default, the three plots generated will look similar to the ones shown in Fig. 2. However, as mentioned previously, the different plot elements can be turned on or off via the plot options menu. To quit the design visualizer tool, enter 0 at the main menu.

8 Using xfoil_only

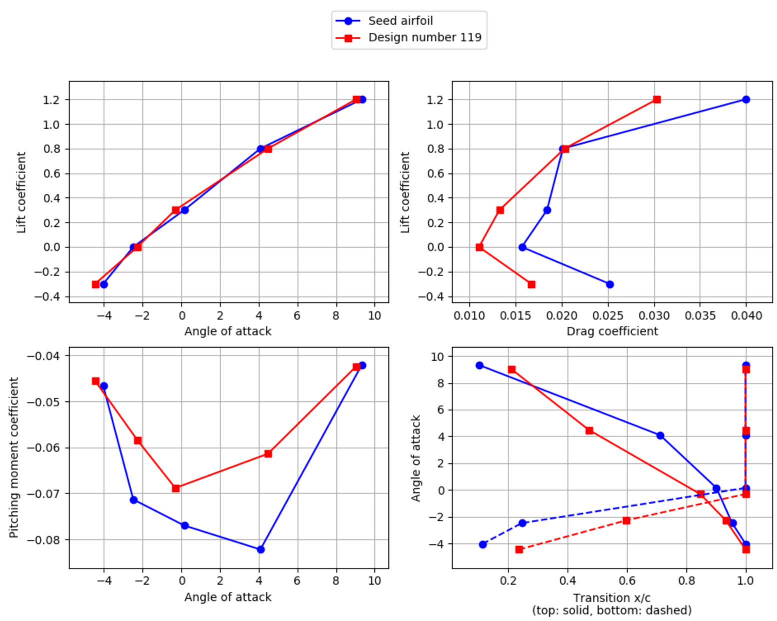
Xoptfoil comes with a tool called xfoil_only, which does exactly what it sounds like it does: it runs Xfoil alone without optimizing. This can be useful for getting an idea of how your seed airfoil will perform before optimizing, for example, or for checking the performance of the optimized airfoil after the optimization. xfoil_only uses the same input file as Xoptfoil, except that many of the inputs are ignored. The relevant inputs are the seed airfoil inputs (which is the one that will be analyzed), the operating points, and the Xfoil settings. Note that if use_flap is enabled, any flap angles specified in the operating_conditions namelist will be applied, even if flap_selection is 'optimize.'



(a) Airfoils



(b) Optimization history



(c) Aerodynamics

Figure 2: Example of plots generated by xoptfoil_visualizer.

When xfoil_only is run, it will first echo the options in the input file. If you have disabled silent_mode in the Xfoil options, Xfoil will print a lot of output to the screen as it does its calculations. Finally, a summary of the geometric and aerodynamic info for the airfoil will be displayed. If the calculations don't converge for any of the operating points, a warning will be shown along with the aerodynamic results.

9 Frequently asked questions

There is a file called FAQ that is included in the Xoptfoil release. You can find answers to frequently asked questions there.

10 Example cases

Two example cases with full input files and plots of the outputs can be in the doc/example_case directory included in the Xoptfoil release. There is also a file in doc/ called 'all_inputs.txt,' which contains all of the possible inputs with comments. It can be used as a template input file if desired; just be aware that many of the inputs may not be needed or appropriate for every case.