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# **SurrModel-Tutorial Documentation**

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This tutorial goes over the basic functionality of the blade-damage repository. The blade damage repository has three main functions:

- Estimate damage equivalent and extreme moments of a wind turbine using already trained data
- Calculate damage equivalent and extreme moments of wind turbine using FAST
- Calculate blade design training point values for use in a surrogate model

In addition, when this code is used with conjunction with RotorSE, fatigue damage constraints can be added to the blade optimization routine either directly in the optimization loop, with an iterative approach, or through use of a surrogate model. These procedures are also described in this tutorial.



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## Estimate blade damage of wind turbine design using trained data

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The first use of this code that we cover is to estimate the blade damage of a blade design using the data that is provided in this repository. The steps to do this are covered in this section. This procedure depends on the [surrogate-modeling-toolbox](#). This will need to be downloaded and installed beforehand.

First, in the script `run.py`, set:

```
FASTinfo['opt_with_surr_model'] = True
```

And make sure that all the other options in the block are set to `False`. Next, set:

```
description = 'trained_data'
```

If you desire to use the data set provided in this repository. Alternatively, you can go into `FAST_Files/Opt_Files/` and change the `trained_data` folder to match the string set to `description`. If another data set is being used, make sure the name of the folder that contains the data matches the `description` string.

The surrogate model uses a number of design aspects of the blade design to estimate the damage equivalent and extreme moments experienced by the wind turbine, so we need to set those values. In the `setupFAST` function in `FAST_util.py`, set:

```
FASTinfo['FAST_template_name'] = 'testWT'
```

Next, in the `initialize_dv` function, set the control point values of the chord and twist distributions. The control points are equally spaced from the root of the blade to the tip, and define [Akima](#) splines which are used to determine the chord and twist values at any point along the length of the blade. Additional information about [Akima](#) splines can be found [here](#). In the `get_bladelength` function (also in `FAST_util.py`), set the blade length. In the `choose_wnd_dir` function, set the turbulence intensity and turbine class.

Check that all of the options in `setupFAST_checks` (function in `FAST_util.py`) are set to `False`. In addition, in the function `setupFAST_other`, set:

```
FASTinfo['calc_DEM_using_sm_no_opt'] = True
```

And all other options set as `false`. Set the wind turbine torque at rated speed. This is done by changing the value of `rated_tq.txt`, which is located in the folder that includes the trained data set.

In `create_surr_model_params`, set what type of approximation model you would like to use. For example, if you want to use radial basis functions, set:

```
FASTinfo['approximation_model'] = 'RBF'
```

In addition, if you desire to use a Kriging function, set the initial hyper-parameter values:

```
FASTinfo['theta0_val'] = [1e-2]
```

With these options set, we can now estimate the damage equivalent and extreme moments of the blade design using a surrogate model. To do so, in the `blade-damage` folder, run:

```
python run.py
```

The damage equivalent and extreme moments will print.

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## Calculate damage equivalent and extreme moments of wind turbine using FAST

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The next use of this code is to calculate the DEMs and extreme moments of a wind turbine using FAST. This functionality depends on FAST. It may be helpful to go over our previous tutorial, which covers how to build a FAST executable, a description of FAST input files, and a cursory explanation of FAST outputs. It also depends on [AeroelasticSE](#), a python wrapper for FAST. This will also need to be installed.

Within the blade-damage directory, find `damage_components.py`. At the top of the script will be the lines:

```
# AeroelasticSE
sys.path.insert(0, '../RotorSE_FAST/AeroelasticSE/src/AeroelasticSE/FAST_mdao')

# rainflow
sys.path.insert(0, '../RotorSE_FAST/AeroelasticSE/src/AeroelasticSE/rainflow')
```

These are the relative paths for subfolders in the AeroelasticSE repository. Set these paths so that they congruent with the placement of your local blade-damage and AeroelasticSE repositories.

Within the blade-damage directory, locate the script `run.py`. In `run.py`, specify:

```
FASTinfo['calc_fixed_DEMs'] = True
```

Make sure that all the other options in that block are set to False. In addition, set the description variable to some appropriate string.

There are a few things that need to be specified in `FAST_util.py`. First, make sure that all the checks in `setup_FAST_checks` are set to False. Next, specify the locations of the virtual strain gages used in the FAST routine. You can do this by setting:

```
FASTinfo['sgp'] = [1, 2, 3]
```

This means that for each wind input file, FAST will run three times. Additionally, we can also set it to be:

```
FASTinfo['sgp'] = [4]
```

Where FAST will only run once for each wind input file. In the `specify_DLCs` function, make sure that:

```
DLC_List = ['DLC_1_2', 'DLC_1_3', 'DLC_1_4', 'DLC_1_5', 'DLC_6_1', 'DLC_6_3']
FASTinfo['rand_seeds'] = np.linspace(1, 6, 6)
FASTinfo['mws'] = np.linspace(5, 23, 10)
```

when calculating the damage equivalent moments. However, for test purposes, you will want to use a small subset of design load cases to make sure that it is working properly without taking too long. An example of a test set is:

```
DLC_List = ['DLC_1_2', 'DLC_1_3', 'DLC_6_1', 'DLC_6_3']
FASTinfo['rand_seeds'] = np.linspace(1, 1, 1)
FASTinfo['mws'] = np.linspace(11, 11, 1)
```

The wind files for the DLC 1.2, 1.3, 1.4, 1.5, 6.1, and 6.3 are included in this repository. The nonturbulent wind files (DLC 1.4, 1.5, 6.1, and 6.3) are found in `WND_Files/nonturb_wnd_dir`, and were generated using [IECWind](#), an NREL tool. The turbulent wind files (DLC 1.2, 1.3) are found in `WND_Files/turb_wnd_dir_A_I` and `WND_Files/turb_wnd_dir_B_I`. These files were generated using the script `create_turb_wnd_files.py` (which is included in this repository), which is python wrapper for [TurbSim](#), another NREL tool.

If the user desires to use other wind input files, they are encouraged to familiarize themselves with [TurbSim](#) and [IECWind](#), and to use our TurbSim python wrapper if a large number of new wind input files are created.

Within this repository, five sets of FAST input files are included. They can be found in `FAST_Files/FAST_File_templates`. In general, the easiest way to use this code is to also use one of these templates. For example, if we want to use the NREL 5MW templates files, in the `setupFAST` function in `FAST_util.py` set:

```
FASTinfo['FAST_template_name'] = 'NREL5MW'
```

The baseline design of these wind turbines are changed in two ways. First, the chord and twist distribution, as well as the blade length, are defined in `FAST_util.py`, and be changed by following the instructions in the previous section. Other aspects of the turbine design are changed directly in the FAST input files. See the FAST user manual for specifics.

If a different set of FAST input files is used, place the files in `FAST_Files/FAST_File_templates` folder, and set `FASTinfo['FAST_template_name']` to the name of the folder. However, it is beyond the scope of this tutorial to go over how to create FAST input files for a wind turbine design.

We are now ready to calculate the damage equivalent moments. In the blade-damage folder, run:

```
python run.py
```

The damage equivalent moment values will be recorded and stored in `FAST_Files/Opt_Files/(description string)`.

---

## Calculate blade design training point values for use in a surrogate model

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Before we can train points to use in the surrogate model, we need to calculate the wind turbine torque at rated wind speed.

Within the blade-damage directory, locate the script `run.py`. In `run.py`, specify:

```
FASTinfo['calc_fixed_DEMs'] = True
```

Make sure that all the other options in that block are set to `False`. In addition, set the description variable to some appropriate string, such as `train_data`.

Within the blade-damage directory, locate the script `FAST_util.py`. There are a few things that need to be specified in `FAST_util.py`. First, make sure that all the checks in `setupFAST_checks` are set to `False`. In the `setupFAST_other` function, set:

```
FASTinfo['save_rated_torque'] = True
```

In the `specify_DLCs` function, set:

```
DLC_List = ['DLC_0_0']
```

From the command line, navigate to the folder that contains `Run.py`. Then, run:

```
python Run.py
```

This command should create a file that contains the torque at rated speed. We can now set up the training point calculations. In `run.py`, specify:

```
FASTinfo['calc_surr_model'] = True
```

Make sure that all the other options in that block are set to `False`. There are a few things that need to be specified in `FAST_util.py`. First, make sure that all the checks in `setupFAST_checks` are set to `False`. Next, specify the locations of the virtual strain gages used in the FAST routine. You can do this by setting:

```
FASTinfo['sgp'] = [1, 2, 3]
```

This means that for each wind input file, FAST will run three times. The training will take longer, but this way there won't be any interpolated data used to train the surrogate model and will result in a more accurate surrogate model.

In the `specify_DLCs` function, make sure that:

```
DLC_List = ['DLC_1_2', 'DLC_1_3', 'DLC_1_4', 'DLC_1_5', 'DLC_6_1', 'DLC_6_3']
FASTinfo['rand_seeds'] = np.linspace(1, 6, 6)
FASTinfo['mws'] = np.linspace(5, 23, 10)
```

when training a full surrogate. However, for test purposes, you will want to use a small subset of design load cases to make sure that it is working properly without taking too long. An example of a test set is:

```
DLC_List = ['DLC_1_2', 'DLC_1_3', 'DLC_6_1', 'DLC_6_3']
FASTinfo['rand_seeds'] = np.linspace(1, 1, 1)
FASTinfo['mws'] = np.linspace(11, 11, 1)
```

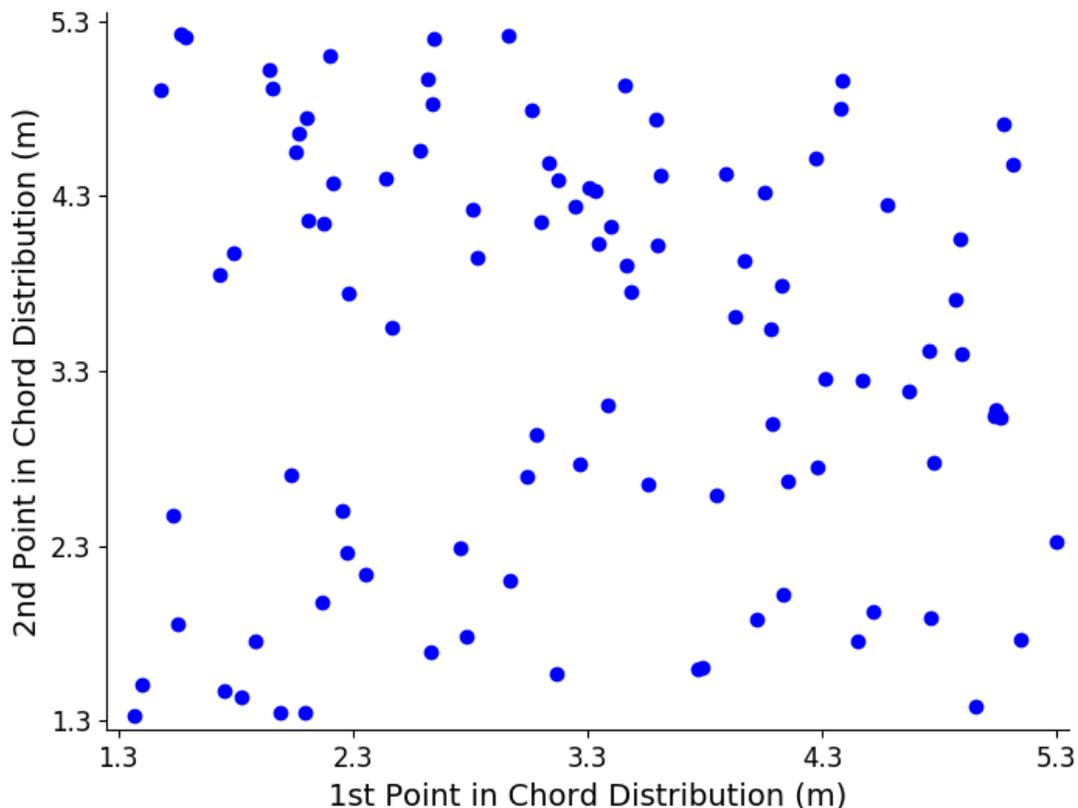
In the `create_surr_model_params` function, specify how many points we will attempt to train in the surrogate model. For example, if we want to train 1000, points:

```
FASTinfo['num_pts'] = 1000
```

Also, make sure that:

```
FASTinfo['training_point_dist'] = 'lhs'
```

An example of 100 points being specified with linear hypercube spacing in two directions is shown below.



**Note:** Initial work supported a full factorial option (linear) as well as linear hypercube spacing (lhs), but functionality has only been developed for lhs.

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In the setupFAST function, specify which reference turbine design template will be used. For example, if we want to use the WindPACT 5.0 MW reference turbine:

```
FASTinfo['FAST_template_name'] = 'WP_5.0MW'
```

Note that if a WindPACT reference turbine is used, also set:

```
FASTinfo['set_chord_twist'] = True
```

We can now train the surrogate model. An example of doing this would be to include the following lines in a batch script:

```
#SBATCH --array=1-999 # job array size
echo ${SLURM_ARRAY_TASK_ID}
python runOPT.py ${SLURM_ARRAY_TASK_ID}
```

on the supercomputer. The size of the array will depend on the number of training points. Once all the points have been trained, use the function combine\_results (in the script FAST\_Files/combine\_sm\_results.py). This is needed if only one wind turbine is being used to train the surrogate model, or a number of wind turbines. Set opt\_file\_srcs as the string descriptions defined in run.py, and opt\_file\_dest as the description used in run.py when we next use the surrogate model. Note that some data may not have been recorded because for some turbine designs, FAST may not have been able to converge. This function does have some nice functionality in that it can handle these cases.



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## Blade design optimization with fatigue damage constraints

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We now explain how to optimize a blade design using fatigue damage constraints. We outline three methods:

- Optimize with FAST calculation in the loop
- Optimize with fixed DEMs
- Optimize blade design with surrogate model for fatigue damage

To begin, clone this branch of [AeroelasticSE](#). AeroelasticSE is a python wrapper for FAST. In addition, clone this branch of [RotorSE](#). RotorSE is an engineering model for the analysis and optimization of wind turbine rotors. Both AeroelasticSE and RotorSE are dependent on a number of sub-packages, so make sure these are installed correctly. Next, compile a FAST executable. Instructions on how to do this can be found in our previous [tutorial](#).

### 4.1 Optimize with FAST calculation in the loop

To optimize a blade design while performing the FAST calculation within the optimization loop, find the RunOPT.py script in the RotorSE repository. It will be in the src/rotorse folder. Next, set:

```
FASTinfo['opt_with_FAST_in_loop'] = True
```

Once the training data has been created, set:

```
FASTinfo['opt_with_surr_model'] = True
```

and all other options set as false in that block. You can now run the optimization routine with the command:

```
python runOPT.py
```

Note that unless a small number (1-3) of wind input files are used, this optimization will take a very long time to complete. Even with a small set of wind input files, this routine is still very computationally expensive.

## 4.2 Optimize with fixed DEMs

The next method we describe is to optimize a blade design using fixed damage equivalent moments, to do this, follow the steps in calculating damage equivalent and extreme moments of wind turbine using FAST. Once this has been done, locate the file RunOPT.py in the RotorSE repository. It will be in the src/rotorse folder. Finally, set:

```
FASTinfo['opt_with_fixed_DEMs'] = True
```

and all other options set as false in that block. You can now run the optimization routine with the command:

```
python runOPT.py
```

If you desire to iteratively improve the blade design and update the damage equivalent moments used in the optimization, the process is relatively straightforward. Once the optimization is complete, set the optimized values of the design variables in the initialize\_rotor\_dv function in FAST\_util.py (in the blade-damage repository), recalculate the damage equivalent moments, and rerun the optimization with the updated DEMs.

## 4.3 Optimize blade design with surrogate model for fatigue damage

First, in the script run.py, set:

```
FASTinfo['opt_with_surr_model'] = True
```

And make sure that all the other options in the block are set to False. Next, set:

```
description = 'trained_data'
```

If you desire to use the data set provided in this repository. Alternatively, you can go into FAST\_Files/Opt\_Files/ and change the trained\_data folder to match the string set to description. If another data set is being used, make sure the name of the folder that contains the data matches the description string.

In create\_surr\_model\_params, set what type of approximation model you would like to use. For example, if you want to use radial basis functions, set:

```
FASTinfo['approximation_model'] = 'RBF'
```

In addition, if you desire to use a Kriging function, set the initial hyper-parameter values:

```
FASTinfo['theta0_val'] = [1e-2]
```

With these options set, when RunOPT.py is run again, it should create the surrogate model before the optimization begins.

## CHAPTER 5

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### Indices and tables

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