User manual: MATLAB implementation of the QSQH synthetic model of near-wall turbulence

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Abstract

This manual describes a resource allowing to easily use the Quasi-Steady-Quasi-Homogeneous (QSQH) theory, which describes the dominant mechanism (or one of the dominant mechanisms) by which large-scale turbulent motions affect the turbulent flow in the immediate vicinity of the wall. The QSQH synthetic model is a synthetic turbulence model that for a given large-scale component of the wall friction generates a near-wall turbulent velocity field as described by the QSQH theory. Its MATLAB implementation described in this manual is a combination of MATLAB code and an internal database. It accepts a user-provided input of the wall friction and produces an output database consisting of samples of a velocity field, the statistical properties of which are that of the field predicted by the QSQH theory on the basis of the statistics of the large-scale component of the wall friction represented by the input. The code corresponds to the up-to-date version of the QSQH theory (Chernyshenko, S. 2021, J. Fluid Mech., **916**, A52, doi.org/10.1017/jfm.2021.180). Two currently provided internal databases allow the maximum output box of streamwise $\times$ spanwise length $\approx 200 \times 120$ wall units, with the upper side of the box at about 100 wall units from the wall. The flow statistics as predicted by the QSQH theory can be easily calculated by standard tools without the need of any QSQH derivations per se.

1 Introduction

1.1 System Requirements

- Environment: MATLAB 2023b or later.
- RAM: at least 16 GB.
- Disk Space: at least 25 GB

1.2 Installation

1. Download the "`QSQH_tool.rar`" from Github, and the "`test_dataset.rar`" from Google drive.
2. Extract the files and folders in these two rar files to the same folder. This folder will be the main folder of the QSQH tool.
3. Check that the files

- `Interface.m`
- `Excute_code.m`
- `InputParameters.txt`
- `QSQH_model_1D.m`
- `QSQH_model_3D.m`
- `y_ref.mat`.

are in the main folder and the subfolder "`QSQH_model`". These files are the main body of the QSQH synthetic model implementation.

The "`progressbar.m`" script, which will also be in the folder, has been downloaded from MATLAB FileExchange. (Steve Hoelzer (2023). progressbar (`https://www.mathworks.com/matlabcentral/fileexchange/6922-progressbar`), Retrieved December 19, 2023.)

4. The main folder should also contain folders

    - `input_friction_field_test`
    - `output_1D_test`
    - `output_3D_test`
    - `universal_velocity_field_1D_test`
    - `universal_velocity_field_3D_test`

    with the test versions of the input friction field and the universal velocity field, as well as the reference output, which is used to validate the test output.

2 Test of the installation

1. Launch MATLAB. Open the file "`InputParameters`". Check the the parameters are exactly as such:

    - `Lx,2.513274122871834e+04`
    - `Lz,9.424777960769379e+03`
    - `xmax,0`
    - `zmax,0`
    - `ymin,0`
    - `ymax,50`
    - `test,true`
    - `starting_loop,1`
    - `file_separator,\`

2. Open and run "`Interface.m`". Wait until the end of the calculation. On an average laptop it should take about 2 minutes. Make sure the MATLAB current folder is the main folder, that is the folder where the downloaded files were extracted.

3. Open the file "`InputParameters`" again. Only change the the following parameters:

    - `xmax,204`
    - `zmax,120`
    - `ymax,5`

4. Open and run "`Interface.m`" again. Wait until the end of the calculation. On an average laptop it should take about 15 minutes.

5. Open "`Stats_calculator.m`" and press Run.

6. Check the resulting plots of the mean velocity and the root mean square of the fluctuation velocity obtained by the calculation together with the reference data, and a plot of two point correlations with the reference data. If they coincide, the installation was successful.

3 Using the tool

Both the input data and the universal velocity fields used in Section 2 were for testing the installation. They should be replaced with the working versions.

A universal velocity field file is a representation of the hypothetical 'universal' near-wall velocity field that is independent of the Reynolds number, large-scale geometry of the flow and the large-scale motions, as described by the QSQH theory. Two such files are currently available as a part of the implementation of the QSQH synthetic model. They can be simply downloaded and will not require any further effort from the user:

- 1D universal velocity field.
- 3D universal velocity field.

Extract the folders in the `rar` files to the main folder of the QSQH tool. More universal field data files might be provided in the future.

The input data, however, should be prepared by the user specifically for the flow of interest. The input data must be the friction field which is obtained from the wall shear stresses of the flow of interest. The velocity field of this flow must be statistically homogeneous in x and z directions. The user needs to obtain the wall shear stresses $\tau_x^+(x^+, z^+)$ and $\tau_z^+(x^+, z^+)$ in wall units, from the temporal snapshots that have huge time interval from each other, for example, approximately one flow-through time.

The snapshots of $\tau_x^+(x^+, z^+)$ and $\tau_z^+(x^+, z^+)$ must be stored in the form of MATLAB matrix files of the size of $N_x \times N_z$, where N_x and N_z are the number of grid points in stream-wise and span-wise directions of the wall friction field. Note that $N_x \times N_z$ must be the same as the grid points of the velocity field from which the friction field is obtained. The user needs to take a note of the size of the stream-wise and span-wise domain in wall unit, L_x^+ and L_z^+ for later use. The matrix files should be named as: "`tau_xxxxx.mat`" where "`xxxxx`" stands for the time step or the index of the snapshot. The snapshots should be sufficient so that the friction field is statistically representative. The number of snapshots denoted N.

Create a new subfolder "`input_friction_field`" in the main folder of the QSQH tool. Store the files of the snapshots of the friction field in this subfolder. Also create two new subfolders "`output_1D`" and "`output_3D`" in the main folder of the QSQH tool. The input data is ready for use.

3.1 Input parameters

Apart from the input data of the friction field, the input parameters of the tool must be changed accordingly to the input data and the universal velocity field used. The input parameters of the tool are stored in "`InputParameters.txt`". Open this `txt` files in MATLAB. On the left of the comma, there are the names of the input parameters, and on the right of the comma, they are the values of these input parameters.

`InputParameters_1D.txt`:

- `Lx` stands for the size of the stream-wise domain L_x^+ of the input friction field in wall unit.
- `Lz` stands for the size of the span-wise domain L_z^+ of the input friction field in wall unit.
- `xmax` stands for the user-defined size of the stream-wise domain $x_{\max}^+$ of the output synthetic velocity field in wall unit. Set $x_{\max}^+ = 0$ for 1D output. As for 3D output, the maximum value of $x_{\max}^+$ is suggested to be 204, larger $x_{\max}^+$ for the current version of tool will not yield more useful output data. This value is dependent on the universal velocity field used in the calculation, therefore, this value could be set larger for the new universal velocity field provided in the future.
- `zmax` stands for the user-defined size of the span-wise domain $z_{\max}^+$ of the output synthetic velocity field in wall unit. Set $z_{\max}^+ = 0$ for 1D model. For the same same as `xmax`, the maximum value of $z_{\max}^+$ is suggested to be 120.
- `ymin` stands for the user-defined closest wall-normal position to the wall $y_{\min}^+$ of the output synthetic velocity field in wall unit. You are free to choose within the wall-normal range of $y^+ \in \{0, 100\}$.
- `ymax` stands for the user-defined outermost wall-normal position $y_{\max}^+$ of the output synthetic velocity field in wall unit. You are free to choose within the wall-normal range of $y^+ \in \{0, 100\}$. Note that $y_{\max}^+ > y_{\min}^+$.
- `test` tells the model whether this upcoming run is for the test of the installation, the file names of the output for the test will be marked with the ending "`test`". Set it to true for the test, or false for proper run.
- `starting_loop` stands for the starting loop of the calculation, denoted b_{start}. Set $b_{\text{start}} = 1$.
- `file_separator` stands for the file separator of the system. For example, it is "\" for Windows system, and "/" for the Linux system.

With all the above ready, run "`Interface.m`" to generate the synthetic velocity field for the flow of user's interest.

3.2 Output of the model and post-process

The output files are in the form of "`.mat`" files. The output of the 1D QSQH synthetic model will be the instances of the synthetic velocity profiles in the wall-normal direction, where the outermost position is at $y_{\max}^+$ as defined in "`InputParameters_1D.txt`". The output matrix files are of the size: $N^* \times N_\tau^* \times N_y^*$, where N_t^* is the number of snapshots of the input friction field, and N_τ^* is the number of points sampled from each snapshot of the friction field, therefore, $N_t^* \times N_\tau^*$ yields the number of instances generated by the model. Each instance has the wall-normal grid that

$$y_{\min}^+ < y^+ < y_{\max}^+$$

with N_y^* grid points. The wall-normal grid is obtained from the grid of the base flow of the universal velocity field provided in this tool. The base flow is available at Johns Hopkins Turbulence Databases. Note that $N_y^* = 104$ for $y_{\max}^+ = 100$ and $y_{\min}^+ = 0$.

The output of the 3D QSQH synthetic model will be the instances of the synthetic velocity field which has the grid of the size:

$$\begin{gathered} -x_{\max}^+/2 < x^+ < x_{\max}^+/2 \\ y_{\min}^+ < y^+ < y_{\max}^+ \\ -z_{\max}^+/2 < z^+ < z_{\max}^+/2 \end{gathered}$$

with the grid spacing $\Delta x^+ = 12$ and $\Delta z^+ = 6$. The wall-normal grids of the 1D and 3D output are the same. The output matrix files are of the size: $N^* \times N^*_\tau \times N^*_x \times N^*_z \times N^*_y$, where $N^*_x \times N^*_z \times N^*_y$ are the grid points of the synthetic velocity field in x, z and y directions. For $x^+_{\max} = 204$, $z^+_{\max} = 120$, $y^+_{\max} = 100$ and $y^+_{\min} = 0$, $N^*_x \times N^*_z \times N^*_y = 18 \times 21 \times 104$.

The file "`Stats_calculator.m`" allows to calculate some basic statistics such as mean velocity profile, squared root mean square of the velocity fluctuation and two-point correlation coefficients in (x, z) directions, of the output synthetic velocity field. The functions and features of this file can be further derived to produce more flow statistics.

Due to the large scales in the input friction field, the 3D QSQH model has to implement the expand/compress of the grid of universal velocity field in (x, y, z) directions, and rotation of the grid, as described by the QSQH theory. The synthetic velocity field is obtained by interpolating the expanded/compressed and rotated universal velocity field onto a grid whose size is defined by the user, $x^+_{\max} \times z^+_{\max} \times (y^+_{\max} - y^+_{\min})$. As $x^+_{\max} = 204$ and $z^+_{\max} = 120$ is set by the user, there are potentially "`NaN`" at the edge of the grid of some instances of the output field, which suffers from extreme expansion/compression and rotation of the grid of the universal velocity field. Open file "`Stats_calculator.m`", go to the bottom of the file and uncomment the last section. This section provides the function of presenting the probability of the appearance of "`NaN`" on the (x, z) positions of the output field. Figure 1 is an example of using this function on the reference output that was introduced for the test of installation.

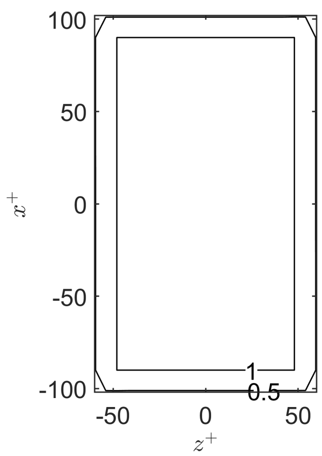

Figure 1: Probability of meaningful data point among all the (x, z) grid points of the reference output.

The area covered by the level of 1 is the area containing no `NaN`, which is:

$$-90 < x^+ < 90$$
$$48 < z^+ < 48$$

On the edge of the grid, there is a 50% chance for "`NaN`" to appear.