

Turbulence control in a mixing tank with PIV

by

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ABSTRACT

This paper describes and evaluates a closed loop turbulence control device for a mixing tank. The idea is to improve the mixing process by controlling the value of a turbulence quantity. The controller output is the rotation speed and the change in rotation speed is considered to change also the value of the turbulence quantities. The feedback signal is measured with a Particle Image Velocimeter. The measurement result can be any turbulence quantity which can be derived from PIV vector fields. The turbulence quantity is measured as a spatial average over the area of interest in an instantaneous vector field. The turbulence quantity is also smoothed by a moving average for a certain number of vector fields from time series of measured vector fields. An ordinary fixed parameter closed loop PI controller is used. The time constant of the controller is slower than the time constant of the flow process, so trim adjusting of the mixing in a spatially and in-time-averaged manner is the only feasible method.

A series of tests were made to evaluate the developed controller. As the controlled turbulence quantity for this case, a modified Reynolds stress was calculated from vector fields by taking the absolute value. The controller then kept constant the value for this modified Reynolds stress by changing the rotation speed. The response of the system to the change in the set value of the turbulence quantity was first tested. In all tests the controller produced a stable response. The modified Reynolds stress value was stabilized. The second test was a disturbance test in which high-viscosity liquid was poured into the vessel. The liquid was sucrose-water solution in two different concentrations. These tests show that the controller could also stabilize the effect of the higher-viscosity liquid on the controlled quantity. The evaluation of the tests shows the feasibility of the idea of mixing process control using spatially and in-time-averaged turbulence quantities as controlled variables.

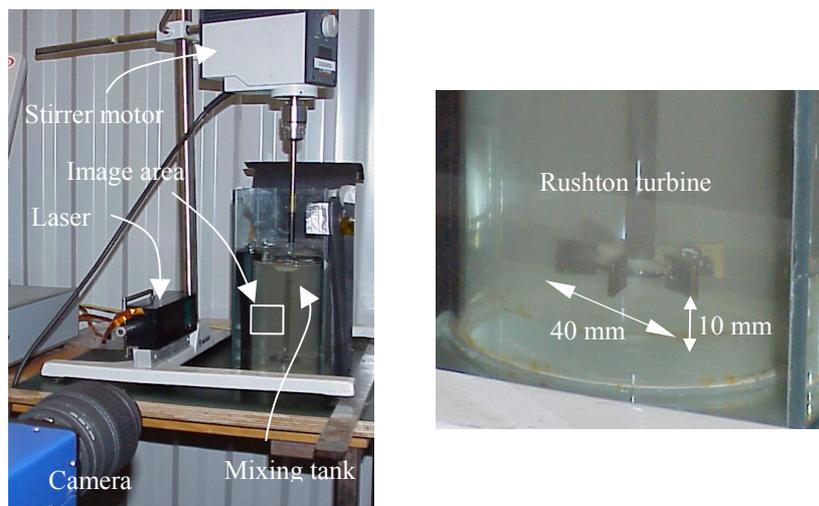


Figure 1: Measurement and control setup. Left, overview of devices; right, details of Rushton turbine.

1. INTRODUCTION

The purpose of this work is to study and demonstrate the capabilities of closed loop turbulence control in a mixing tank. Most turbulence control literature considers cases in which drag reduction (Lumley and Blossey 1998 and Gad-El-Hak 1994) or flow separation prevention or some other means are used to reduce the skin friction or the turbulence level (Tardu, 2001) or to delay transition (Fukunishi and Ebina, 2001). Flow control is reviewed by Gad-el-Hak (1989, 1999), turbulence control by Lumley and Blossey (1998) and control of combustion instabilities by McManus et al. (1993). The driving economic force to study flow control has been the minimization of drag of flying objects. The drag is proportional to power consumption and operation costs. The typical current published results indicate drag reduction gains in the neighborhood of 5%-10% for boundary layer flows. However, theory indicates possible gains of 50%. Thus, current knowledge rarely supports the practical use of the boundary layer control.

The choice of an adequate actuator appears to be also a difficult problem. Actuators can roughly be grouped into three classes: aerodynamic actuators, acoustic actuators and inlet flow modulators. A number of actuator solutions are given in the literature. A few examples of different actuators are investigated in Rathnasingham and Breuer (1997), Kim and Song (1999), Carlsson and Lumley (1996) and McManus et al. (1993).

More profitable applications for turbulence control can be found in industrial devices. In many mixing processes, for example, the properties of a fluid change with time and the adaptation of the turbulence properties to reality is done by experience. Proper control of turbulence properties can easily enhance the process efficiency significantly in the same way as the combustion performance can be increased with active control (McManus et al. 1993). The use of closed loop turbulence control for a backward-facing step flow is described flow in Piirto and Saarenrinne and Lai et al. (2002).

Particle Image Velocimetry gives a new possibility for the active control of turbulence in transparent fluids. The repetition rate of the image grabbing and the computation time of the vector fields restrict its use as an adaptive closed loop trim adjustment controller. Its clear advantage is that different velocity and length scales can be estimated directly from the vector fields and flow structures can be recognized. The control actions can, however, be based on the time mean values of some time interval which is a multiple of the frame rate of the PIV system.

2. MEASUREMENT SETUP

The control tests were made in a small cylindrical mixing tank with a six-blade Rushton turbine (diameter 40 mm, 10 mm above the flat tank bottom). The dimensions of the tank are: height 180 mm and diameter 90 mm. There were no baffles. The tank is made of glass and enclosed in a rectangular box to reduce optical distortions. A laboratory mixer (Heidolph XXX) controllable through an RS port was used to rotate the Rushton turbine. The turbulence control tests were started with pure water and then a ‘step-change’ in the viscosity of the fluid was made by pouring 20%- and 30%- sucrose-water solutions into the vessel. The properties of the fluids used are listed in Table 1. The calculated properties of the mixtures after each sucrose addition are also in Table 1.

Table 1: Fluid properties of the sucrose-water solutions used at 20 °C.

Fluid [% by wt.]	Specific gravity $\times 10^{-3}$ [kg/ m ³]	Viscosity $\times 10^6$ [m ² /s]	Index of refraction [-]
Water	0.9982	1.007	1.333
7.5	1.0297	1.201	1.344
9.6	1.0379	1.269	1.348
11.5	1.0423	1.345	1.350
20.0	1.0829	1.799	1.364
30.0	1.1290	2.828	1.381

The PIV device consists of a double-cavity Nd-YAG laser (2×400 mJ) working at 532 nm wavelength, a laser light guide, laser sheet optics, a cross-correlation CCD camera (1280×1024 pixels) and a computer with software. The turbulence control tests were made with a single camera setup. The frame rate of the camera is 4 Hz in cross-correlation mode.

For turbulence control the measurements were made just above the impeller. Image size was 56x48 mm².

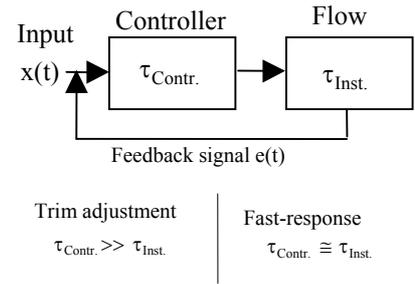


Figure 2: Schema of a fixed parameter feedback controller (McManus et al. (1993)).

3. CONTROL SETUP

A closed loop fixed parameter PI controller was constructed using a controller (a separate PC), an actuator (Heidolph stirrer motor) and a feedback measurement device (PIV). The only tunable parameter in this setup was the rotation speed of the mixer motor. It was assumed that by changing the rotation speed also with the PIV, measurable turbulence quantities could be controlled. The time constant of this controller is very slow (several seconds) compared to the flow process time constant. The set value for the trim adjustment controller used was measured as the moving average of a turbulence quantity and it was compared to the feedback measurement value. The set value $x(t)$ for the rotation speed can be calculated from the following definitions.

$$x(t) = x(t-1) + K_p [e(t) - e(t-1)] + K_i e(t) \quad (1)$$

$$e(t) = \Psi_{sp} - \Psi_{ma}(t) \quad (2)$$

$$\Psi_{ma}(t) = \frac{1}{N_{ma}} \sum_{k=0}^{N_{ma}-1} \Psi(t-k) \quad (3)$$

K_p and K_i are the coefficients for the gain and integration terms in the controller formula. The control output $x(t-1)$ and the control error $e(t-1)$ are the previous control cycle values. Ψ is the instantaneous turbulence quantity, Ψ_{sp} is the set point value and Ψ_{ma} is a moving average value of N_{ma} measurements. The instantaneous turbulence quantity Ψ was measured and calculated from PIV vector fields. All instantaneous vector fields were validated and smoothed. The estimate for the fluctuation fields was then calculated from them by subtracting the moving average velocity field. The value for the turbulence quantity Ψ was then calculated for an area of interest as a spatial average

$$\Psi(t) = \frac{1}{(N_{x_2} - N_{x_1} + 1)(N_{y_2} - N_{y_1} + 1)} \sum_{i=N_{x_1}}^{N_{x_2}} \sum_{j=N_{y_1}}^{N_{y_2}} \Psi(i, j, t) \quad (4)$$

which was then submitted to the controller.

A modified Reynolds stress was used in these tests as a controlled variable and as a feedback signal to the controller. The modified local moving average Reynolds stress was calculated from the formula

$$\overline{uv(i, j)} = \frac{1}{N_{ma}} \sum_{\xi=1}^{N_{ma}} |u(i, j, \xi)v(i, j, \xi)| \quad (5)$$

The absolute value of this Reynolds stress describes better the magnitude of the shear stress field after averaging than the real value. The turbulence quantities were averaged over a period of 50 seconds and the control cycle was 2.5 seconds. The moving average was then estimated for 20 samples. A detailed description of the controller can be found in Piirto and Saarenrinne.

4. RESULTS

Several test runs were performed to find correct values for the coefficients K_p and K_i of the controller (see definition (1)). For short time periods (tens of minutes) it was relatively easy to find suitable values, but for longer times there seems to be some kind of occasionally appearing instabilities in the flow field which require modification of the coefficients. Two different tests were then performed after the parameter tuning. The response of the controller to the step change in set value and to the change in viscosity of the fluid was tested (disturbance test).

The response of the system to the change in the set value was tested first. The set value for the modified Reynolds stress was changed from 0.05 to 0.07. In Figure 1 it can be seen that the modified Reynolds stress reaches the set value and also that the rotation speed of the stirrer smoothes down. In Figure 4 is shown the response for a larger step change from 0.07 to 0.10. The set point response shows some low frequency fluctuation, which could be minimized by more carefully tuning the controller coefficients K_p and K_i . The instantaneous modified Reynolds stress (not in scale) shows strongly fluctuating values that precede the smoothed value by twenty counts.

When the set value was lowered from 0.10 to 0.08, the rotation speed decreased and the modified Reynolds stress value achieved smoothly the set value (Figure 5).

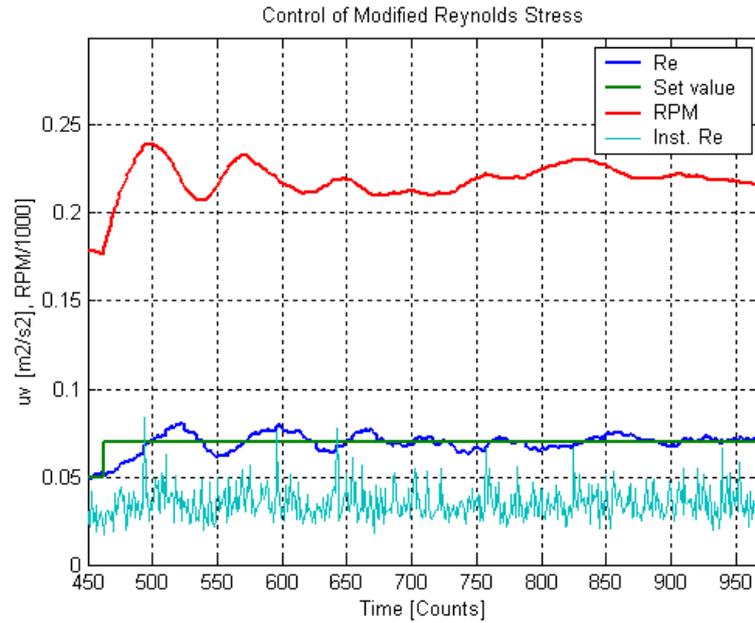


Figure 3: Response of the controller to the step change in set value from 0.05 to 0.07.

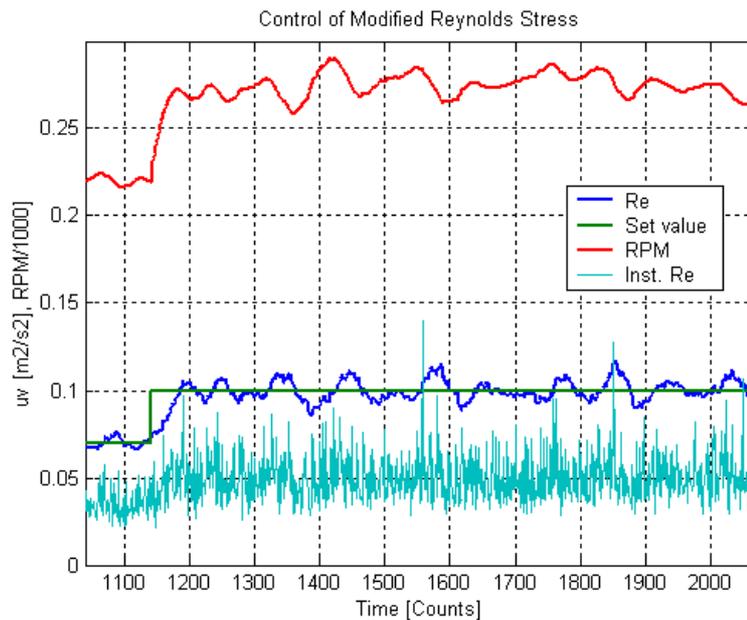


Figure 4: Response of the controller to the step change in set value from 0.07 to 0.10.

Additional high-viscosity liquid (water-sucrose solution) was poured into the vessel for the second test. Two different sucrose-water solutions were made. The first addition was a 20 % sucrose-water solution with the kinematic viscosity of $1.799 \times 10^{-6} \text{ m}^2/\text{s}$ and the second a 30 % sucrose-water solution with $2.828 \times 10^{-6} \text{ m}^2/\text{s}$ kinematic viscosity. The estimated final sucrose concentrations after the mixing were 7.5 % and 9.6 % and the viscosities were $1.201 \times 10^{-6} \text{ m}^2/\text{s}$ and $1.269 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. The final concentrations were checked by refractive index measurement. The results were in line with Table 1. The controller could compensate the change in the Reynolds stress, as shown in Figure 6. The measured Reynolds stress value increased strongly when the liquid addition was made at time 3300 counts (not in time units). The controller lowers the rotation speed directly after the rise in the Reynolds stress value. After some mixing time the liquids were mixed and the rotation speed and the Reynolds stress values settled. The Reynolds stress remains at the original value in spite of the higher

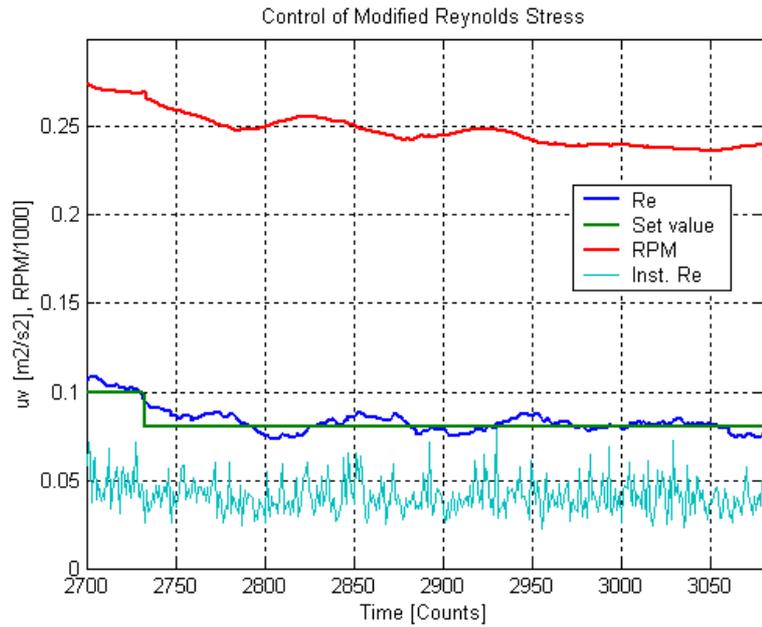


Figure 5: Response of the controller to the step change in set value from 0.10 to 0.08.

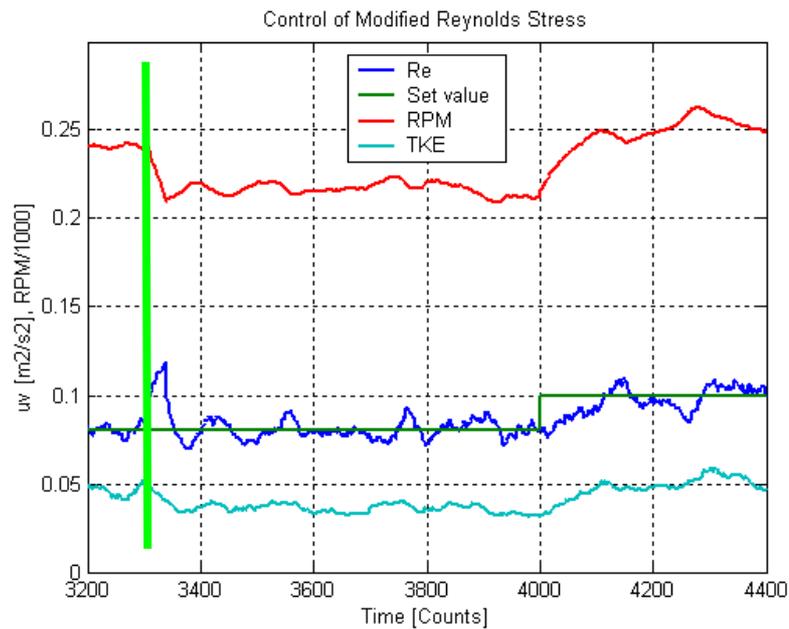


Figure 6: Response of the controller to the change in the fluid viscosity at time 3300 counts (green line).

viscosity of the liquid. After this experiment the set value was increased again to 0.1 in order to allow a new sucrose addition to further increase the viscosity.

The second addition of 30% sucrose water solution was made at 4420 counts. The controller decreased the rotation speed and the Reynolds stress values decreased rapidly to the set value (Figure 7). This is presumably partly because of the stabilizing effect of the higher viscosity on the flow field. The mixer stays stable over 200 counts (500 seconds) and starts to oscillate for an unknown reason. Around the time value 4780 counts there is a peak in rotation speed that is a result of a typical technical problem in data transfer to the stirrer motor.

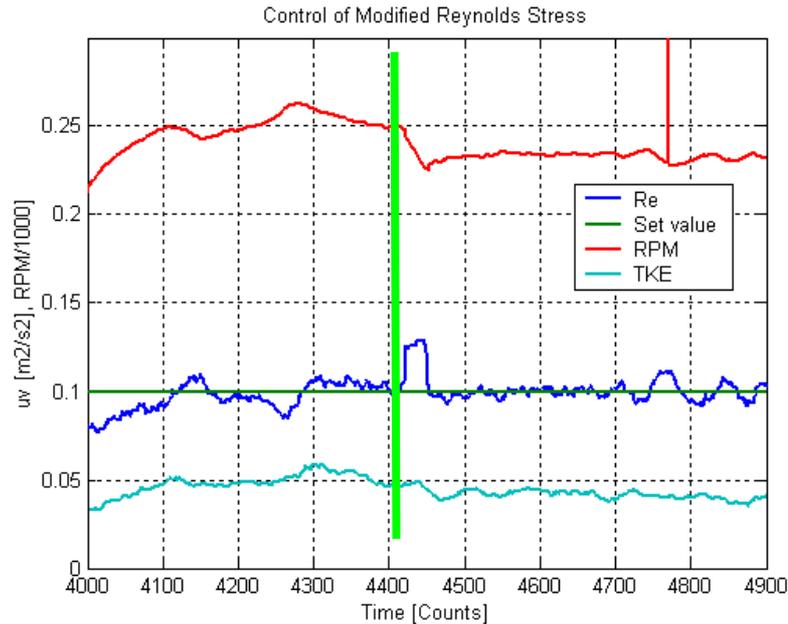


Figure 7: Response of the controller to the change in the fluid viscosity at time 4420 counts (green line).

5. CONCLUSIONS

The control of turbulence is usually considered a practice to reduce surface friction or prevent flow separation. The use of turbulence control in industrial devices has not been the subject of much evaluation. Improving the efficiency of a mixing process, for example by controlling directly the values of turbulence quantities, can have many advantages.

A turbulence control device for a mixing process was designed in this paper. A fixed parameter closed loop PI controller was used. Several tests were made to check the feasibility of the method. The response of the method to step changes in set values was tested and also the response of the controller to step change in the viscosity of the liquid. These experiments confirm that the PIV can be used as a probe for the closed loop trim adjustment turbulence controller. Actually it has many advantages compared to the other devices. The instantaneous vector field can be a source of multiple instantaneous or time mean turbulence quantities, which are impossible to measure by other means. The disadvantage of the method is its very long response time and rather complex construction.

It was also noted that the simple PI controller could not control the random long-term disturbances in the mixer flow field. Perhaps a more sophisticated controller with adjustable parameters could improve the performance.

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