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Model free active flow control of a simplified car model

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Abstract:

A model free control (MFC) approach is presented and used to symmetrize the unstable wake flow of a simplified car model named Ahmed body. Such unstable phenomena with regards to the space-time evolution of the low pressure wake vortex core, is known to increase the global drag of square back vehicles. Results highlight the ability of a MFC to reduce the wake symmetry breaking phenomena by using lateral blowing slit jets. A model free control scheme derived from (Fliess and Join, 2013) is proposed and a tuning procedure is suggested. At last experimental results on an Ahmed body in wind tunnel are provided.

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Keywords: Air flow control, Ahmed body, model free control, experimental results

1 INTRODUCTION

Improving the vehicle fuel economy can be investigated using different approaches such as hybridization, vehicle body mass reduction, etc. This work focusses on active drag reduction. In layman terms, the global drag is mainly related to the average pressure difference between the front and the back of the body. Modifying the wake flow on the back of the vehicle can lead to a reduced drag. Flow dynamics around a real car is very complex to model due to the shape of the vehicle. The Ahmed body is a simplified physical car model generally used as generic body by the fluid mechanics community to test control strategies in wind tunnel test bench. It shares some interesting properties with some real cars such as the wake symmetry breaking. Depending on some very small external disturbances, the wake flow switches between two different mirror configurations. Recent works in fluid mechanics illustrated that forcing the wake flow to a symmetric configuration leads to a drag reduction (Li, 2017; Li et al., 2016).

Several approaches can be designed to control the wake of the vehicle. In this study, air knife blowers located on the right and left side of the Ahmed body are used.

On a control point of view, the problem is challenging. The physical equations of the air flow dynamics are difficult, not

to say, impossible to derive analytically. CFD models also can be obtained but their complexity is not suitable for control purposes. Black box modelling is also tedious due to a strong non-linear behaviour, in open loop external disturbance induces switches between different steady state position. In order to overcome these difficulties a model free control approach is considered.

Several model free control framework have been investigated. For instance, PID and adaptive control can be used. In this work a controller inspired by the “intelligent-PID” from (Fliess and Sira-Ramírez, 2003) is proposed. It only relies on two parameters that can be easily tuned in practice. However, the approach being model free, the closed loop performances cannot be mathematically demonstrated.

2 EXPERIMENTAL SETUP

The considered square back Ahmed body and the associated sensors are depicted in the Fig. 1. It comprises several pressure sensors at the back of the body and a drag balance able to measure the 6 components of the aerodynamic tensor. A PIV (Particle Image Velocimetry) system is also installed in order to underline the bi-stable wake flow behaviour along a transverse plane.

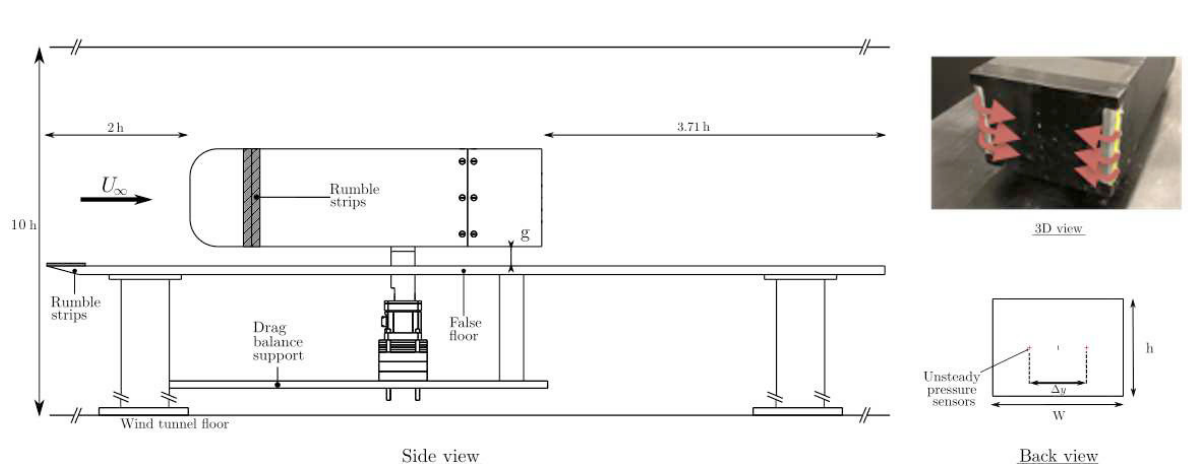


Fig. 1: Experimental setup

The chosen actuators are air blowers mounted on the rear vertical edges of the Ahmed Body. Thanks to the Coanda effect, they allow to blow in the transversal plane of the rear back Ahmed body (cf. picture in upper right part of Fig. 1).

3 PROBLEM STATEMENT

As now clearly admitted in the literature, (Cadot et al., 2015; Grandemange et al., 2013), the instantaneous flow past rectangular bluff body can induce wake symmetry breaking (Wsb) phenomena for some configurations depending mainly of the ground clearance, g . The present work aims at controlling the bi-stability behavior of such turbulent wake

past a square-back Ahmed body with a width to height aspect ratio, w/h of 1.346 and a ground clearance $g = 0.2h$. For a body aligned with the flow, the asymmetric structure is demonstrated to flip randomly between two asymmetric states (named hereafter #P and #N corresponding to positive/negative drift, C_y or lateral pressure variation, ΔC_p), each the mirror image of the other. The Wsb modes correspond to the two stable bifurcated branches resulting from an instability of the stable symmetric wake as shown in Fig. 2.

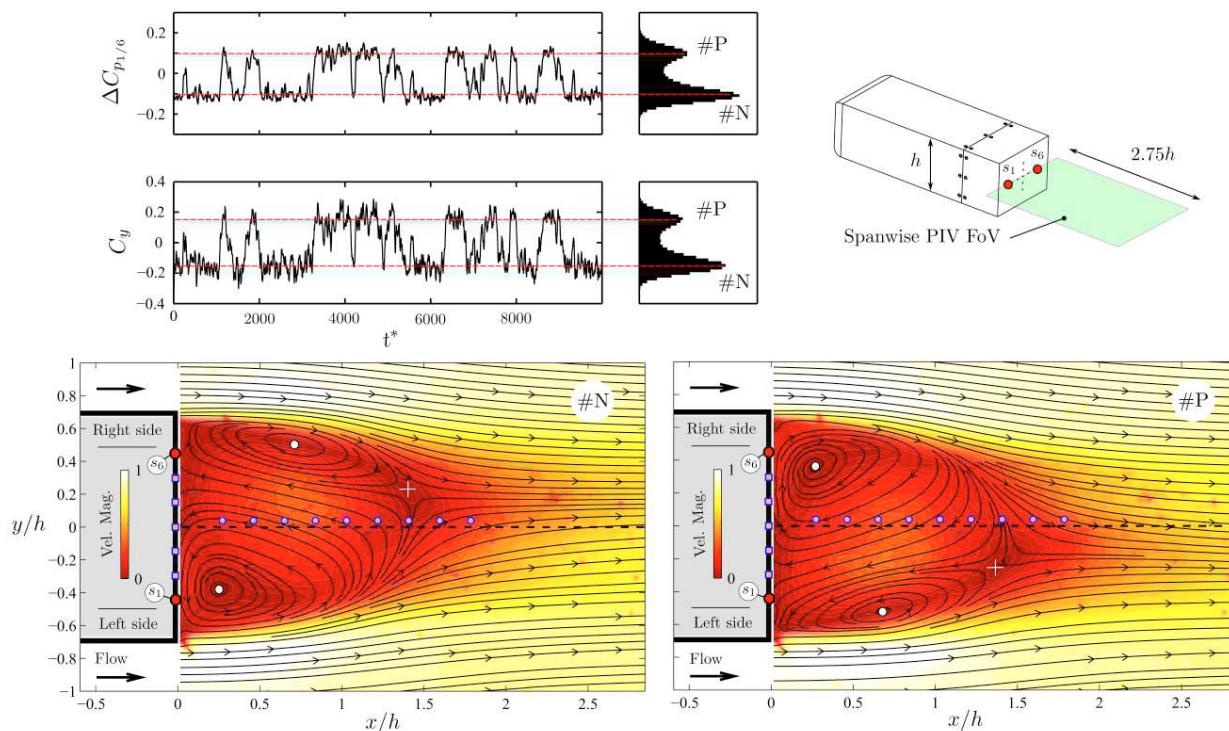


Fig. 2. Illustration of the wake symmetry breaking phenomenon.

The Wsb phenomena, due to the alternative motion of the vortex cores (denoted by the white circles in Fig 2.), induce a strong increasing of the drag. The goal of the present paper is to control the wake using lateral slit jet actuators in order to symmetrize the wake and as consequence to reduce the global drag force by using a model-free control approach.

4 MODEL-FREE CONTROL

Developing a model can be costly due to the required instrumentation and/or the required engineering time. In this work, the system behaviour is too complex to be easily modelled using the physics equations. Black box modelling from measurement data could also be investigated, but due to the encountered non-linear effects, this task can be tedious. As a result, a model free control approach is preferred.

4.1 Proposed Model-Free control law

Several model free control approaches have been developed, for instance adaptive control (Wang et al., 2018) or the well-known PID when empirically tuned. The retained approach is derived from the “intelligent” controllers proposed in (Fliess and Sira-Ramírez, 2003). This approach is based on a so-called ultra-local model of the output signal y . In (Fliess and Sira-Ramírez, 2003), the original model was chosen as a n -th order integrator. Instead, it is suggested to use the following second order ultra-local model:

$$y^{(2)}(t) = F(t) + \frac{2}{\tau} y^{(1)}(t) - \frac{2}{\tau^2} y(t) + \alpha u(t) \quad (1)$$

With F an unknown signal to be estimated, τ and α two parameters to be fixed by the practitioner and u the control.

The considered approach is therefore not totally model-free since the model (1) is used to compute the control law. But the model is chosen a priori, almost regardless of the system dynamics, by fixing the parameters τ and α . The actual system dynamics is in fact gathered by the unknown signal F .

The suggested control law is:

$$u(t) = -\frac{\hat{F}(t) - y_r^{(2)}(t) - \frac{2}{\tau} y_r^{(1)}(t) - \frac{1}{\tau^2} y_r(t)}{\alpha} \quad (2)$$

With \hat{F} an estimate of the unknown signal F and y_r a C^2 reference signal to be tracked.

Compared to the original control law proposed in (Fliess and Sira-Ramírez, 2003), the control law (2) does not need the additional Proportionnal Integral Derivative term. It has only two parameters, its tuning is expected to be simpler.

The closed loop dynamics is given by:

$$e^{(2)}(t) = F(t) - \hat{F}(t) + \frac{2}{\tau} e^{(1)}(t) - \frac{2}{\tau^2} e(t) \quad (3)$$

If the unknown signal is perfectly estimated ($F(t) = \hat{F}(t)$), then the output will track the reference signal exactly with the dynamics of a second order system whose poles are located at $-\tau^{-1}$. The parameter τ allows to fix the desired dynamics of the closed loop and is not related to the dynamics of the system.

According to (3), assuming the closed loop stability, the steady state error is null if the steady state estimation error $F(t) - \hat{F}(t)$ is also null. It should be noticed that the unknown signal gathers all forms of disturbances that could affect the actual system. So a null steady state estimation error is sufficient to ensure the rejection of disturbance.

4.2 Estimation of the unknown signal F

Several approaches can be used to estimate the unknown signal F . In this work, an ALIEN filter is suggested (De Miras et al., 2013). Over a very short period of time, the unknown signal is assumed to be constant $F(t) = F$. The filter is obtained by first computing Laplace transform of (1):

$$\frac{F}{s} = \frac{2(y(0) - sY(s))}{\tau} + s y(0) + y^{(1)}(0) - s^2 Y(s) - \frac{Y(s)}{\tau^2} + U(p) \quad (4)$$

With s the Laplace operator, Y and U the Laplace transform of y and u .

Taking twice the derivative of (4) with respect to s allows getting rid of the initial conditions $y(0)$ and $y^{(1)}(0)$. Finally, the estimation of the unknown signal is obtained by computing the inverse Laplace transform of the resulting expression. The whole process is conducted using symbolic computation software for sake of simplicity. The obtained results are:

$$\hat{F}(t) = \int_{t-T}^t (I_u(u(t), t) + I_y(y(t), t)) dt \quad (5)$$

With

$$I_u(u, t) = \frac{30\alpha}{T^5} (-t^2 u(t)(T-t)^2) \quad (6)$$

$$I_y(y, t) = \frac{60}{T^5} (t^2 y(t) + y(t)(T-t)^2) + \frac{60}{T^5} (T-t) \left(-4t y(t) + \frac{2t^2 y(t)}{\tau} + \frac{t(T-t)}{\tau} \left(-2y(t) + \frac{t y(t)}{2\tau} \right) \right)$$

The alien filter (5) is obtained as a function of the continuous time variable t . Its implementation on a computer requires to use sampled signals, and to approximate the integral using a numerical quadrature.

To the best of the authors' knowledge, there is no study yet available on the effect of this discretization method on the closed loop performance. The filter being used for control purposes, it is expected that the steady state estimation error reaches zero for a constant reference signal (assuming the closed loop stability). Let us assume that:

$$\lim_{t \rightarrow +\infty} F(t) = F_\infty \quad (7)$$

With F_∞ a constant.

In steady state, according to (1), the output y and the control u are constant due to the system equilibrium. Let us denote by y_∞ and u_∞ these constant. In that context, let us remark that $I_u(u_\infty, t)$ is a polynomial in t of degree 1 and $I_y(y_\infty, t)$ is a polynomial in t of degree 4. The steady state value of the unknown signal is therefore obtained by computing the integral of a 4th order polynomial.

$$\hat{F}_\infty = \int_{t-T}^t (I_u(u_\infty, t) + I_y(y_\infty, t)) dt \quad (8)$$

As a consequence, the numerical quadrature used to implement the Alien filter (5) on a computer must be of order greater or equal to 4 in order to ensure a perfect steady state estimation. In this work, the chosen numerical quadrature is a Newton-Cotes formula of order 4. The sampling period T_s being fixed, the size of the integration window T is adjusted to the minimum required by the Newton-Cotes method: $T = 4 \cdot T_s$.

Let us note $y_k = y(k \cdot T_s)$, $u_k = u(k \cdot T_s)$ and $\hat{F}_k = \hat{F}(k \cdot T_s)$. The discretization of the integral (5) is computed using symbolic computation software. The result is a linear Finite Impulse Response filter:

$$\begin{aligned} \hat{F}_k = & \frac{7}{24T_s^2} y_k + \frac{9T_s^2 + 24T_s \tau - 4\tau^2}{24T_s^2 \tau^2} y_{k-1} \\ & + \left(\frac{1}{4\tau^2} - \frac{1}{4T_s^2} \right) y_{k-2} - \frac{-9T_s^2 + 24T_s \tau + 4\tau^2}{24T_s^2 \tau^2} y_{k-3} \\ & + \frac{7}{24T_s^2} y_{k-4} \\ & - \frac{3}{8} u_{k-1} - \frac{1}{4} u_{k-2} - \frac{3}{8} u_{k-3} \end{aligned} \quad (9)$$

4.3 Control law tuning

First of all, it is necessary to recall that the stability of the closed loop cannot be mathematically guaranteed since the

dynamic of the system is unknown. This remains the main drawback of any model free control approach. As a consequence, the practitioner should be very careful when tuning the control loop.

The suggested tuning procedure is:

Step 1: Given T_{srt} the expected step response time of closed loop; fix $\tau \approx \frac{T_{srt}}{4.671}$. In practice it is often safe to start with a large T_{srt} compared to the open loop response time.

Step 2: Choose a reference signal y_r with relatively a low dynamics to start with.

Step 3: choose a large value for α . From (2), it is clear that this allows to reduce the amplitude of the control.

Step 4: Iteratively decrease the value of α until an admissible closed loop behavior is obtained.

This tuning methodology has been successfully experimented on different systems but may have to be adapted to the actual system specificities

5 PRELIMINARY EXPERIMENTAL RESULT

The proposed control law is applied to the Ahmed body. The control objective is to control the drift using two knife blowers installed on each side of the Ahmed body. The blowers are connected to fast on-off pneumatic valves controlled by the binary signals z_r and z_l , Fig. 3.

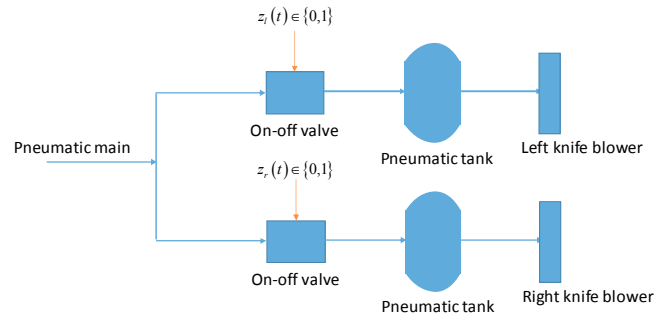


Fig. 3: Schematic of the pneumatic actuators

These binary signals are generated using a Pulse Width Modulation signal whose modulation is given by the control u . The left blower is activated when $u(t) < 0$ while the right blower is activated when $u(t) > 0$. The resulting signals are depicted in Fig. 4 for the particular case of a PWM period of 0.1s. This binary signal generation requires the control signal u to be saturated between -1 and 1. The pneumatic tanks have a low-pass filter effect. As a result, the controller output u allows to control the average pressure at the output of the knife blowers.

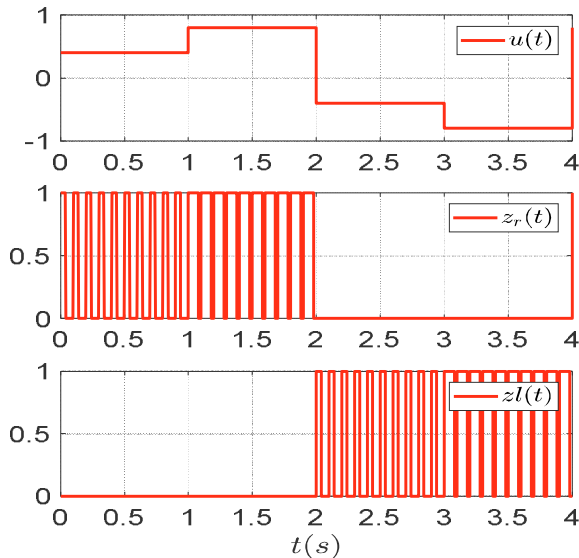


Fig. 4: Binary signal generation using PWM

The wind tunnel is used to generate a wind speed of 20m/s corresponding to a Reynolds number of $Re_h = 2.86 \cdot 10^5$. For these preliminary experiments, the objective is to control the drift so it can track a setpoint. This allows to control dynamically the position of the vortex cores depicted in Fig. 2.

The control problem is challenging since the overall physics depends on phenomena that are distributed in space. The Fig. 2 only represents the averaged velocity fields. In practice, the “vortex shedding” phenomena may generate high frequency drift variations. On a control point of view, they may be assimilated to some measurement noise clearly visible on the open loop response Fig. 5.

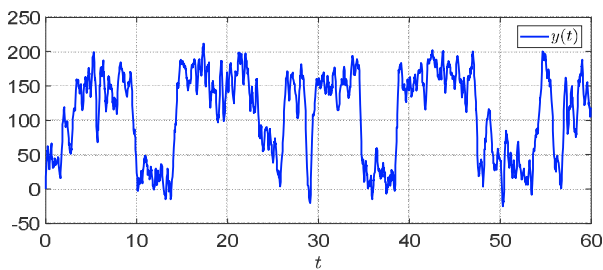


Fig. 5: Drift measurement in open loop

The ultra-local model time constant is chosen as $\tau = 0.1s$ to obtain a step response time of 0.46s. Due to implementation constraints, the sampling period is $T_s = 10^{-3}s$ to allow the PWM signal generation with a period of 0.03s.

The controller is quite sensitive to the vortex shedding. A compromise has to be found between the closed loop tracking performances and the sensitivity to this “noise”. The priority

has been set to the tracking performances. Using the suggested tuning procedure, $\alpha = 5 \cdot 10^5$ is obtained. The results are depicted in Fig. 6. The minimum and maximum setpoint values have been to avoid saturating the control during the steady phases. In order to test the control law robustness, the pneumatic pressure has been decreased to 2.5 bars and the wind speed has been changed to 15m/s. The obtained results are given in Fig. 7. In both cases, despite the noisy measurements, the output follows the setpoint with the expected dynamics.

6. CONCLUSIONS

A model free control law has been proposed. It is based on the framework proposed by (Fliess and Join, 2013). The contributions are a simpler control law, a justification of the quadrature order used to discretize the Alien filter and a tuning procedure. Preliminary results have been obtained for the Ahmed body. It has been possible to control the drift to track a reference signal. The control law is quite sensitive to the vortex shedding which can be assimilated to some measurement noise. Future work will be devoted to the control law improvement (tracking performance and noise sensitivity) and also to the measurement of the drift. At last the proposed control scheme will be tested on a real car.

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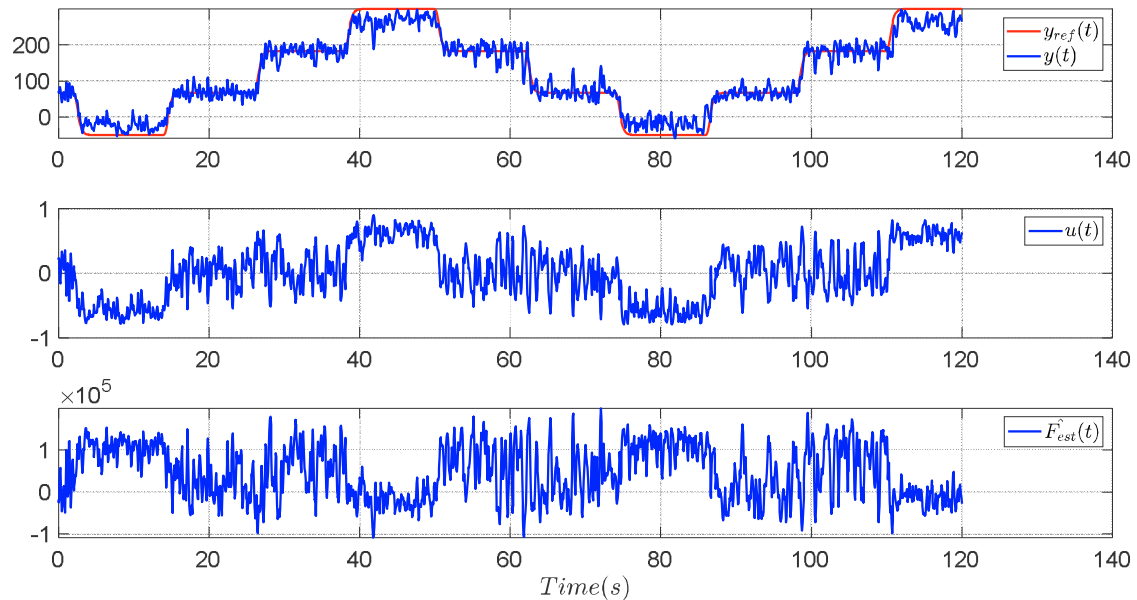


Fig. 6: Closed loop response using a 4bars pneumatic pressure, 20ms/wind

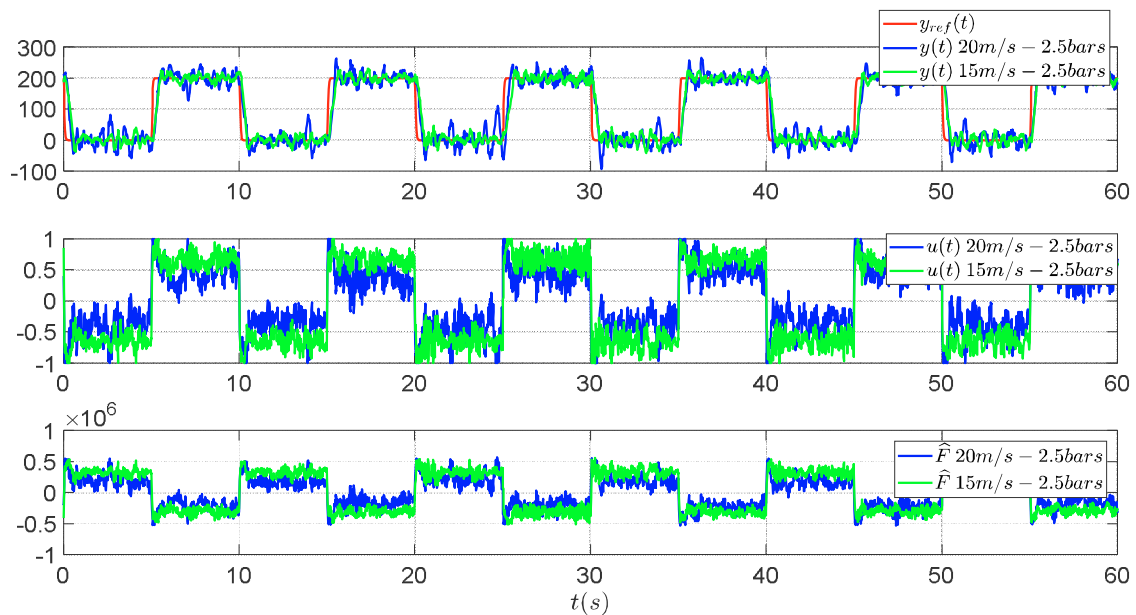


Fig. 7: Closed loop response for 20 m/s at 2.5bars and 15m/s – 2.5bars