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Simulation in the Loop Control of a Planar Hypersonic Wing with a Rigid Control Surface

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Abstract

There have been significant advances in sustained hypersonic flight technologies. Hypersonic vehicles are now considered for sustained atmospheric flight, for example accelerators in access to space systems or for high speed transport applications. All these applications require effective and robust control surfaces, mechanical actuators, and appropriate control strategies to ensure efficient flight trajectories can be followed. Hardware-in-the-Loop-Simulation (HiLS) is an approach that allows the assessment of different control approaches (controllers, actuators, control surfaces) through simulation, reducing the need for costly experiments and flight tests.
This paper presents the development of a HiLS set-up targeted at analysing control systems in hypersonic flows. The simulation component is created using the time accurate hypersonic CFD solver Eilmer, which has been modified to also predict the dynamic response of test hardware.
To verify the HiLS capability a pivoted flat plate, which has been tested as part of previous control experiments at Mach 5.9 is simulated. Analysis of verification tests, with control inputs that match experimental settings shows that the simulation set-up can appropriately re-create the correct dynamic responses for the controlled plate. Next, the HiLS tool is used to analyse different control approaches.
These simulations confirm that simple acceleration based control is not adequate to control the pivoting plate. Next, a new P-D-DD controller, incorporating an additional second derivative term is evaluated. The result is a response with reduced over-shoot and control of the plate at the target angle.
This work confirms the ability of the CFD solver to be used as part of a HiLS set-up. The work also demonstrates the benefits of HiLS in for the design of controllers for hypersonic applications.

Introduction

The last decade has seen significant advances in sustained hypersonic flight technologies. International flight programs [1] have helped push ahead our understanding of scramjets, flight dynamics, and control of vehicles (HiFire4). These flight programs have been highly successful in demonstrating the feasibility of air-breathing inner atmospheric flight and increasing the Technology Readiness Level of hypersonic systems. However, they are costly and not without risk, as demonstrated by the loss of several test vehicles during launch or during the flight tests (e.g. Scramspace, HiFire-5a). Consequently we are continuously seeking better (lower cost, lower risk, scientifically valuable) approaches to gain insight into hypersonic systems and how they interact with the hypersonic flow, through ground-tests and simulation.

An area that is receiving increased attention is the effective control of vehicles at hypersonic speeds. To minimise the risk for the primary experiment, the majority of test flights at hypersonic speeds have used aerodynamically stable arrangements, with coned aft-bodies (e.g. HiFire-1) [8] or even keeping booster rockets attached to the test hardware to increase stability. Only the HyShot Stability Demonstrator [10] and HiFire-4 [1] had a focus on actuators and control systems. In light of propulsion system efficiency and weight being paramount for hypersonic flight vehicles, exploring control systems that are efficient in manipulating the flow to maximise control forces and that can be realised with today's actuators (motors) is an important research question.

The T-USQ facility at the University of Southern Queensland provides a platform for physical experiments in the area of hypersonic control. In the compression-heated Ludwieg tube set-up, it allows testing at speeds up to Mach 7 [3] and for test duration of up to 200 ms. These long test durations (compared to other facilities available in Australia) have allowed experimental tests to analyse fluid-structure interactions [4, 17] and to test actuated models [2]. A necessity to enable these experiments, has been the miniaturisation of the test hardware, which significantly limits the availability of off-the-shelf actuators and gearboxes to suit the planned tests. This in conjunction with the short test time and the associated constraints for developing and tuning control systems has been a challenge.

Hardware-in-the-loop-Simulation (HILS) is an approach by which the plant is replaced by a high fidelity simulation and associated simulated sensors. The approach has become common practice in aerospace since software has become a safety-critical component in flight control [9] and is a common approach in the automotive industry [5]. Within the HiLS framework control systems and control approaches, as well as sensor placement and actuator operation can be evaluated in the numerical/simulation world. The key advantages of this approach are that systems can be evaluated without risking damage or loss of real hardware, that physical models used in the simulation can be altered, and that limits can be exceeded without risk or need for hardware change. This allows a more complete exploration of the control system and it's capabilities.

The aim of the current paper is to report on the development of a HiLS set-up for hypersonic systems. Using the CFD solver Eilmer [6] as a high fidelity plant model it is shown that we can appropriately recreate control experiments. Finally, the performance of different control laws is evaluated and it is shown that using a second derivative term enhances the control response.

Approach

The origin of the HiLS approach can be traced back to the earliest control systems that used inverted plant models. Here a typical verification step would have been to use the inverted model to control the original plant model, thus effectively controlling the simulated plant. However, widespread use has been somewhat limited due to the high computational cost and complexity associated with performing time-accurate transient CFD simulations. To that effect simulating small models and the rapid control actions that are necessary for hypersonic vehicles is an advantage as it limits the required simulation time.

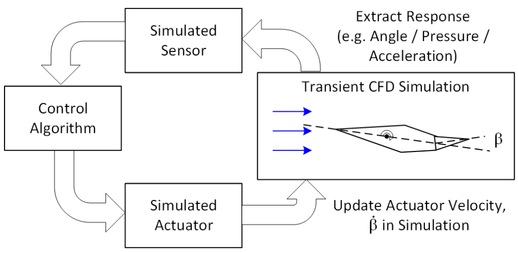


Figure 1: Schematic showing the simulation in the loop (HiLS) setup.

Velocity	Pressure	Temperature
$1005\,\mathrm{m\,s^{-1}}$	743.0 Pa	73.5 K

Table 1: Free-stream flow conditions from experimental tests in T-USQ. The same data have been used for the simulations.

The HiLS setup for the current project is shown in figure 1. In this arrangement, the test model (diamond wing) is pivoting over an axis at approximately $\frac{1}{3}$ chord and allowed to interact with the flow. The flow interaction is simulated using the CFD solver Eilmer, which models the aerodynamics of the problem and also predicts the dynamic response of the wing. From this simulation selected data, currently wing angle, α, wing velocity, $\dot{\alpha}$, and wing acceleration, $\ddot{\alpha}$, are measured and passed to the controller. The controller uses these data in conjunction with the implemented control logic to create an actuator response, currently prescribed flap velocity, $\dot{\beta}$. This actuator response is passed back to the model in the fluid dynamic simulation, which changes the flap angle accordingly. As we are using a transient CFD solver the time-resolved response to the actuator response is realised and the resulting response of the model is passed back to the controller through the simulated sensors.

For the moment we are considering an idealised case, where sensors and actuators respond instantaneously. However, through the incorporation of appropriate state space machines correct time-lags and actuator responses can be realised. Similarly, sensor noise and uncertainty can be added through appropriate numeric noise sources.

When complementing experimental work, the HiLS approach brings a number of distinct advantages. Foremost, the control of physics in the simulation that is not afforded in a real experiment. For the current work, this allows us to use idealised actuators, but more importantly when moving between sub-scale test models and real prototypes, it allows us to correct for inertia and mass that typically scale at different rates than aerodynamic forces. Equally the ability to slow down or stop time allows the evaluation of more complex control strategies that may not be realisable in real-time.

All these advantages, together with the increased insight gained from a fluid dynamic simulation in the form of detailed flow-field data are a significant advantage to controller development.

Experiment and Model Geometry

The experiments were conducted in TUSQ, a compression heated Ludwieg tube located at the University of Southern Queensland in Toowoomba. The TUSQ condition used in this work utilised the Mach 5.9 nozzle and had a total pressure of 1 MPa and a total temperature of 550 K[3]. The distinguishing features of TUSQ are the long test times, in excess of 200 ms, making it well suited for fluid structure interaction and control experiments. For test models with typical oscillation frequencies between 20 and 50 Hz, this allows up to four oscillations to monitor the response to any control input. The free-stream flow conditions used for presented series of experiments are summarised in table 1.

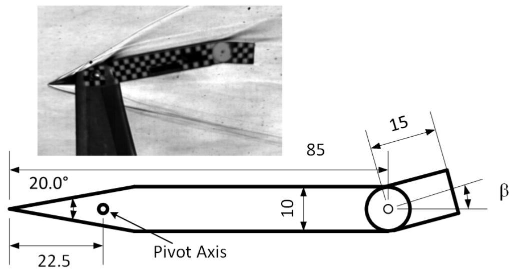


Figure 2: Geometry of model used for controlled experiments and image from experimental tests, reproduced from [14].

Parameter	Value	Parameter	Value
CoG	32.4 mm	Inertia	$1.136 \times 10^{-4}\,\mathrm{kg/m^3}$

Table 2: Geometric and dynamic properties for the model. All values dimensioned for a 2-D model.

The model used in this study was first designed by Stern and has completed a number of experimental campaigns [2]. The model geometry is shown in figure 2 and the corresponding geometric and dynamic parameters are summarised in table 2. During experiments the model is initially positioned in a nose up position and the incoming hypersonic flow is used to start an oscillatory motion. This work and the work by Yamada *et al.* [17] showed that the ensuing oscillations maintain a near-constant amplitude throughout the test time. In their works Buttsworth and Stern [2, 14] demonstrated the ability to both amplify and attenuate the motion. The amplified result is shown by the experimental traces for wing angle, α_{exp} in figure 3. This was achieved by using a PID controller applied to the flap angle, β_{exp}. The target flap angle for this controller was set to $\pm\beta_{max}$ based on the instantaneous wing velocity $\dot{\alpha}_{exp}$ (see [14] for further details). A limitation of these experiments was the inadequacy of the miniature gearbox, which included significant backlash, which resulted in a delay of up to seven milli-seconds between the start of motor movement and flap motion. Furthermore the same backlash allowed the flap to respond to aerodynamic forcing, which gives rise to the somewhat erratic variation in flap angle, β_{exp} seen in the experimental results.

The experimental data presented for wing angle, α_{exp}, and flap deflection, β_{exp}, are obtained by evaluation of the high-speed videos collected during the tests. As such they represent the actual position and shape of the model as seen by the flow [14].

Simulation Set-up

The simulations for the HiLS set-up, to replace the test hardware in the wind-tunnel are conducted using the finite volume CFD code Eilmer [6, 7]. Eilmer has been developed at the University of Queensland specifically for time accurate transient simulations of hypersonic flows in shock tunnels. The Eilmer solver uses the finite volume formulation and is based on the AUSMV family of flux calculators [16]. The conserved quantities are updated explicitly and the time-step is constraint to fulfil the Courant–Friedrichs–Lewy (CFL) criterion to ensure time accurate solution of the unsteady flow. Eilmer is second order accurate in space and time. In the proximity of strong shocks, the EFM scheme [12] is used to increase numerical diffusion and to ensure stability. The solver has undergone extensive verification and validation and has been the work-horse for expansion tunnel simulations at the Centre for Hypersonics at the University of Queensland.

The first adaptation of the solver to work with grid motion was completed by Petrie-Repar [11], and this has been further developed by Qin *et al.* [13]. Details of the implementation are reported by Qin *et al.* Studies by Trudigan [15] showed that this approach yields time accurate results as long as the vertex motion per time step is less than half the respective cell dimension.

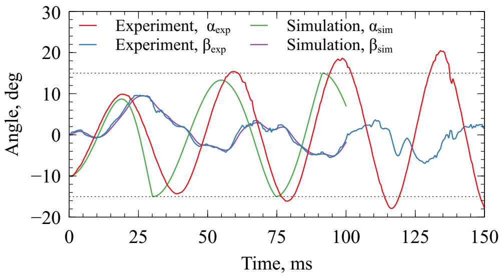


Figure 3: Comparison between experiment and inviscid simulation for the *amplified* case. Flap angle, β is prescribed to match experiment.

For the presented simulations the velocity update time step is identical to the fluid time step and the maximum motion per time step ($\sim$0.0016 mm) is more than two orders of magnitude less than the wall normal cell height (0.75 mm).

For the current proof of concept work, simulations were conducted on two grids. The coarse grid with a total of 800 cells was used for initial evaluation. The solution of a simulation with 150 ms real-time, solved on a cluster with 12 cores in 1.62 hrs using the shared memory version of the code. This allowed for the iterative determination of the control parameters without having to wait for lengthy computations. For final results, a finer mesh with 8050 cells was used. Here the viscous simulations with 12 cores took approximately 32.5 hrs.

Discussion

The discussion of results is split into two parts; first, we conducted simulations to recreate the amplified experiment conducted by Stern and Buttsworth to demonstrate the accuracy of the approach. Next, we complete a HiLS investigation to evaluate new and different control logics to achieve better motion control.

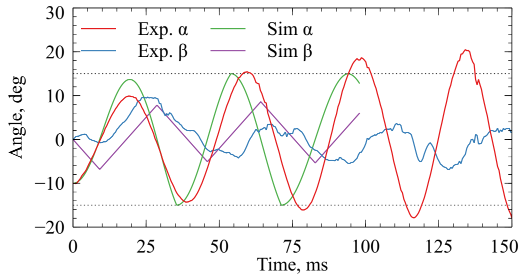
Comparison to Experiments

To demonstrate the capability of the HiLS approach we recreate the amplified experiment reported by Stern and Buttsworth. For these simulations the initial wing angle, α_{sim}, is set to coincide with the first experimental measurement. The flap deflection angle, β_{sim}, is prescribed to follow a smoothed version of the experimentally measured flap deflection.

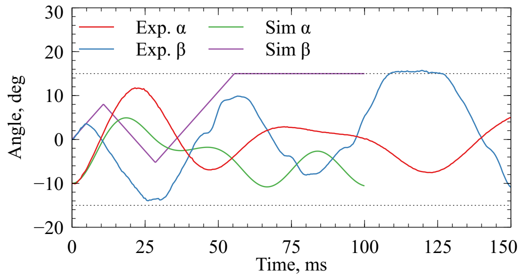
Figure 3 shows the results for the amplified experiment. Considering the results, it is clear that the simulation re-creates the observed trend and that the motion amplitude increases. Notable discrepancies occur during first down motion of the trailing edge ($t = 15\,\text{ms} - 30\,\text{ms}$) and also the third upwards motion ($t = 85\,\text{ms} - 95\,\text{ms}$). Two different effects occur here. In the simulation as the flap is moving upwards, a brief unstart of the flow on the upper side of the model occurs. This is a numerical result due to the resolution and domain size of the simulation. This causes a brief pressure spike and forces the model to turn around and go down again, earlier than it should. This was only noticed after the simulations had been completed, and as the effect is not major, the simulation has not be redone at this stage. The other effect is that the simulated wing motion is limited by bump-stops at $\pm 15°$ (shown as dotted lines in figure 3). These were includes to reflect similar mechanical limits fitted to the physical model. Considering the experimental data, which exceed these positions, it can be seen that these stops had failed during the first cycle or previous tests (this was also seen in the post-test investigation of the model).

Simulation in the Loop based on Initial Control Logic

Figure 4 shows the corresponding graphs, where the flap angle, β is prescribed by a simulated controller that tries to mimic the hardware controller from the experiments. In both cases the



(a) Amplification using Eqn. 1.



(b) Attenuation, using Eqn. 2.

Figure 4: Control of oscillating flap to amplify and attenuate motion.

control actuator is modelled as ideal, meaning that based on control demand a flap deflection velocity, $\dot{\beta}$ of $\pm 750\,°\,\text{s}^{-1}$ is set instantaneously. The control logic for the amplifying and attenuating simulations are

$$\dot{\beta} = \begin{cases} +\dot{\beta}_{max} & \text{if } \alpha >= 0 \\ -\dot{\beta}_{max} & \text{if } \alpha < 0 \end{cases} \tag{1}$$

and

$$\dot{\beta} = \begin{cases} -\dot{\beta}_{max} & \text{if } \alpha >= 0 \\ +\dot{\beta}_{max} & \text{if } \alpha < 0 \end{cases} \tag{2}$$

This is different to the experiment, but this approach was chosen as it approximates the actual relationship between observed wing angle α and flap angle β. The results for the amplifying case show that the simulation quickly approaches a limit cycle motion, impacting the upper and lower stops at $\pm 15°$. In the attenuating case a more rapid control of the flap motion, α is observed, which can be attributed to the reduced lag of the idealised actuator in the simulation. As the second control law, shown in Eqn. 2 is effectively positive feedback, the final state of the actuator, after dampening the oscillations is at the upper deflection limit. This state is reached much more rapidly in the simulation than the experiment.

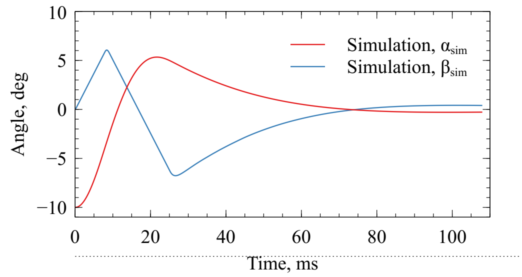
Enhanced Control Logic

Interrogation of the fluid dynamic simulation, which enables the control moments acting on the wing and flap to be separated, revealed that the control moments generated by the wing at high angles far outweigh the moment that can be generated by the flap. This is despite the higher flap angle (up to $\pm 35°$ relative to incoming flow for maximum wing angles) and the increased moment arm.

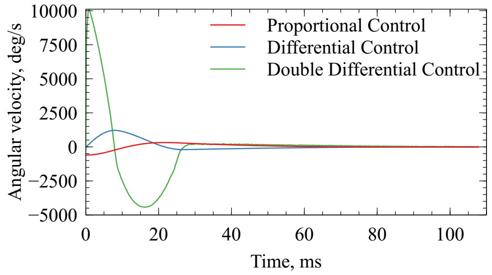
Thus, our next move was to investigate a PID controller for wing angle, α, and to incorporate a double differential term, based on wing rotational acceleration, $\ddot{\alpha}$. It was also found that the integral term of the controller is not contributing significantly. The resulting control law for the actuator is:

$$\begin{aligned} \dot{\beta} &= K_P\,\alpha + K_D\,\dot{\alpha} + K_{DD}\,\ddot{\alpha} \\ \dot{\beta} &= \begin{cases} \min(+\dot{\beta}_{max}, \dot{\beta}) & \text{if } \dot{\beta} \geq 0 \\ \max(-\dot{\beta}_{max}, \dot{\beta}) & \text{if } \dot{\beta} < 0 \end{cases} \end{aligned} \tag{3}$$

where K_P, K_D, and K_{DD} are the gains for the proportional, differential, double differential term respectively, equal to 60, 500,



(a) Plate and flap motion.



(b) Contributions of different control components to prescribed flap deflection rate, $\dot{\beta}$.

Figure 5: Angular control achieved with enhanced control law.

and 40×10^{-3}. The values for $\pm\dot{\beta}_{max}$ are set to $\pm 750^\circ\,\mathrm{s}^{-1}$ to match the capabilities of the currently available actuators. The HiLS results for this enhanced actuator control law and the corresponding contributions from the different controller terms are shown in figure 5. The operation of the resulting controller can be split into two phases. Initially ($t < 30\,\mathrm{ms}$), the *DD* term dominates and the controller works to counteract the acceleration of the flap, $\ddot{\alpha}$. Considering that the *DD* term is negative, this corresponds to feed-forward control with a 180° phase advance. Hence during the initial phase, when the wing is accelerating upwards, the flap moves in the upwards direction too, to counteract the anticipated overshoot. This allows the controller to arrest the wing motion after just over half an oscillation. After this point, for $t > 30\,\mathrm{ms}$, the *P* and *D* terms become significant and take over the control, returning the wing smoothly to the intended target angle.

Using the HiLS setup we have been able to extract data with respect to the relative importance of the control force contributions from the wing and flap, that would not have been easily accessible from the experiment alone. Using the insight provided with these data allowed us to propose and evaluate a new control law, which allows rapid attenuation of the wing oscillations, while staying within the limitations of currently available actuators.

Future Work

The work presented in the current work is a proof-of-concept demonstration for HiLS of hypersonic models using the CFD solver Eilmer as the simulation component. We plan to build on this work to develop a more representative simulation framework that includes the real dynamics of motors, gearboxes, and electronic controllers to analyse improved control strategies for hypersonics applications.

Conclusions

The current paper presents the development of a Hardware-in-the-Loop-Simulations (HiLS) set-up. The HiLS setup uses the CFD solver Eilmer both for the time-accurate solution of the fluid dynamics and to solve the dynamic response of the controlled object. Through comparison to experiments it is demonstrated that this set-up can capture the dynamic response of a controlled pitching flap in Mach 5.9 flow. Using the additional insight, gained from the fluid-dynamic simulations, it is possible to develop a new control law, incorporating a double derivative term that can dampen oscillations in less than half a period.

Acknowledgements

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