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Evaluation of Control Methods for Thermal Roll Forming of Aerospace Composite Materials.

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ABSTRACT

With increased demand for composite materials in the aerospace sector there is a requirement for the development of manufacturing processes that enable larger and more complex geometries, whilst ensuring that the functionality and specific properties of the component are maintained. To achieve this, methods such as thermal roll forming are being considered. This method is relatively new to composite forming in the aerospace field, and as such there are currently issues with the formation of part defects during manufacture. Previous work has shown that precise control of the force applied to the composite surface during forming has the potential to prevent the formation of wrinkle defects. In this paper the development of various control strategies that can robustly adapt to different complex geometries are presented and compared within simulated and small scale experimental environments, on varying surface profiles. Results have found that traditional PID control can be utilized, although its robustness under varying conditions reduces performance in situations that are far from the tuned scenario. This causes the PID controller to struggle with geometries containing surfaces with high frequency surface variations. To enable more robust control an H∞ based controller was therefore developed for the thermal roll forming process. Simulated results show that while the individual implementation of both controllers were successful in achieving the desired response, the H∞ based controller was able to perform better across a wider range of desired surface profiles.

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1. INTRODUCTION

The prevalence of composites in the aerospace industry is increasing due to their high specific strength and stiffness and low densities, allowing the formation of high performance structural components. Since the development of carbon fibre in the 1970's, composites in commercial aircraft have seen a percentage composition increase of 5-6% in the Airbus A320 in 1985, to 35-50% in the Boeing 787 in 2008 [1]. This rise in composite utilization has generated a demand for larger and more geometrically complex components, thus incentivizing the development of a more diverse range of primary and secondary manufacturing techniques [2].

Research at The University of Nottingham on the use of thermal roll forming (TRF) on uni-directional UD laminates is being carried out with industry[2]. This method is based around roll forming practices used in polymer forming. However, the application to composites is focused as a secondary process and applied to UD laminate coupons generated using an Automatic Fibre Placement, AFP, method. In TRF a force is applied to the layers using a roller in an attempt to distribute the pressure evenly throughout the structure. The issue with such an approach is the formation of wrinkles in and in between the laminates that may be related to interply shear characteristics. These wrinkles reduce the structural strength of the components and ultimately lead to unexpected failures [3]. The current focus of research on TRF is to profile and characterize factors that contribute to the creation of defects such as wrinkles within this UD laminate example, where the main factors being considered are temperature, machine feed rate and the application of force.

This paper looks at controlling the application of force to the UD laminate example. The automated system consists of a roller with a force sensor attached to a pneumatic actuation system and translated via a linear drive system. To prevent the formation of wrinkles, it is believed that a constant force must be applied to the composite surface [3]. A robust control system is therefore required that can adjust to a range of varying geometry profiles, and the changes in force application that result from this. The use of PID controllers is wide spread in industry today. However, these types of controllers are generally only useful within the limit operational range from which they are derived. The use of a H∞ system has the potential to provide a more robust control across a greater operational range. A H∞ controller is therefore developed and implemented within a simulation environment similar to that of the final system to be evaluated. The performance of the H∞ controlled system is then compared to the performance of a derived proportional-integral-derivative (PID) controller based on desired operational characteristics before application on an experimental test system will begin.

Section 2 puts the work into context and defines the plant model used within the H∞ controller development. Section 3 will cover an overview of the development of the controllers including their setup and background. Section 4 will detail the results of the simulations and show comparisons of the open loop and closed loop systems under specific conditions relevant to the forming process. Sections 5 and 6 are the discussion of the results and conclusions respectively.

2. BACKGROUND/CONTEXT

This section looks at the formulation of a basic digital plant model for implementation in the formation of control methods and simulation purposes.

2.1. Digital Plant Model

The developed model is based on an example pneumatic actuation model, created by Mathsworks [4] and implemented in Simulink Model using MATLAB software. It is constructed using functions from the Simscape foundation library and masked subsystems, as the more SimHydraulics library does not function with pneumatics. The input to the system is a constant pressure from an air supply, and the output is the force from the cylinder onto the composite surface. The corresponding input pressure,P_I, to a desired output force is the product of the desired force ,F_O, and the area of the cylinder bore, A, shown in Eq.(1) and Figure 1:

$$P_I = F_o A \tag{1}$$

The Simulink model used in this study consists of: A Controlled Pneumatic Pressure Source that outputs a desired constant pressure and is controlled via a physical signal; A 3-way directional valve to control the path of the air supply; a double-acting pneumatic cylinder. The cylinder's physical force output is countered by a reactive force, F_R, that is the product of the output stroke of the piston and a spring constant value, shown in Figure 1.This simulates the composite material response from the force applied by the roller as given as:

$$F_R = Lk \tag{2}$$

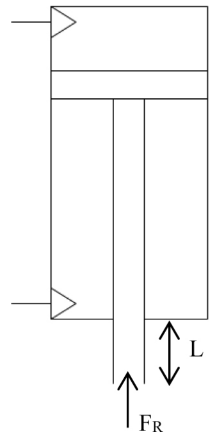

Figure 1. Free body diagram of actuator and reactive force.

A mod.stiff/trapezoidal solver (ode23t) was implemented.

2.2. Plant model Validation

A physical experiment was conducted to validate the digital plant model generated using the Simulink package in the MATLAB Software. The experiment rig utilized is shown in Figure 2. An air supply providing 0 to 6 bars of pressure is regulated via a manual pressure regulator and actuates a 20 mm bore pneumatic cylinder, therefore a maximum of 120 N can be applied onto the load cell. The load cell is interfaced to a computer, via a PhidgetBridge Input board, to register the output force. The load cell is placed on top of a pair of translating plates with compression springs in between them. The compression springs simulate the stiffness response from the forming medium and provide a reaction force against the actuation of the cylinder.

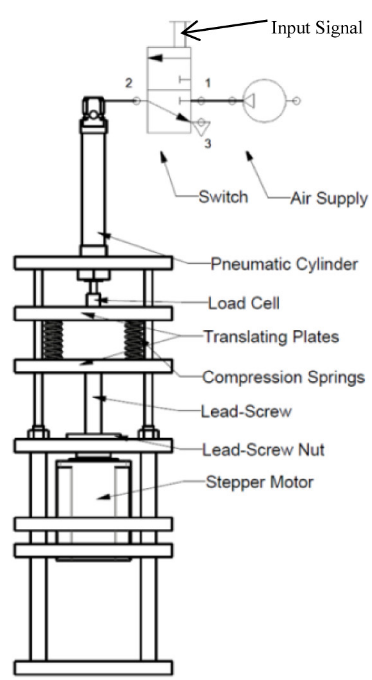

Figure 2. Physical test cell schematic

The validation trials investigated the output response of the physical system to a sudden step input, where the step input is generated by turning on the air supply to the pneumatic cylinder using the manual push/pull pneumatic switch. The possible error for the reading on the load cell is ±10g and therefore it is not a considerable amount. The variation in one of the pressure readings obtained by the load cell for a step input of 0 to 98.1N is shown in Figure 3:

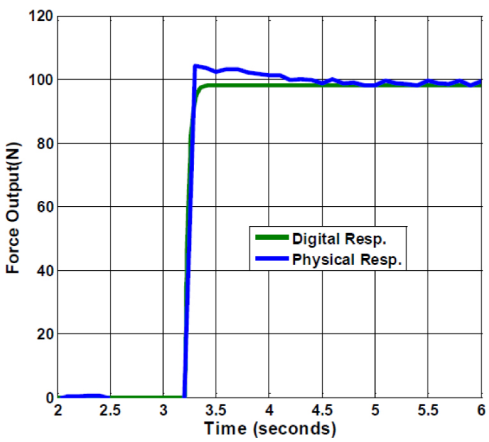

Figure 3. Comparison of digital and physical pressure application and response

This force step output was obtained by inputting a pressure of approximately 5 bars. The results show that the digital simulation appropriately validates the physical response of the system as they both respond in a similar manner. Differences are due to compressibility of the air that is not accounted for in the model. This was done to keep the model as simple as possible and therefore develop a controller with a lower order of magnitude with plant error accounted for as part of the H∞ controller development. The response times to step from 0 to 98.1N are equal as are the magnitude of the steady-state value reached.

3. CONTROL DEVELOPMENT

In the following section the two main control systems are outlined below and a brief overview of the desired response case that these are compared.

3.1. Desired Controller Response

The controllers' objective is to apply a constant output force onto the surface of the composite by varying the input pressure and comparing this with the applied value and potentially resultant values from a load cell. A controller is required as the geometry of the manufactured structure could be of a relatively complex nature and contain surfaces of fluctuating frequency where resulting variable contact forces may lead to the formation of defects in the material or incomplete geometries being formed. Figure 4 shows the general closed loop block diagram for the system, where to achieve control of the system the desired force, F_D, is subtracted from the measured force, F_A. The error is then passed through the PI or H∞ controller in block, C_r, and resulting command signal sent to the valve.

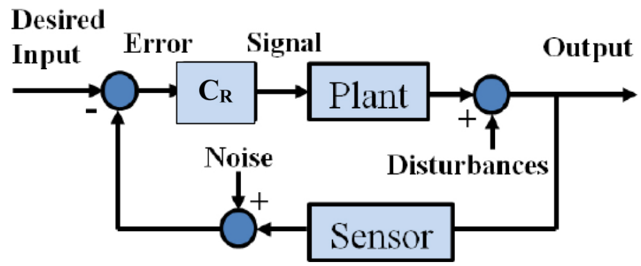

Figure 4. General control block diagram for the system

The optimal response from the system generates a desired force output in as short of time as possible without any overshoot before reaching a steady-state. The overshoot increases the probability of the formation of wrinkles as the extra force would generate a crater under the roller. It is therefore favorable to have a slightly faster response than an over-damped response. The desired shape of the response, in comparison to other responses, is shown in Figure 5:

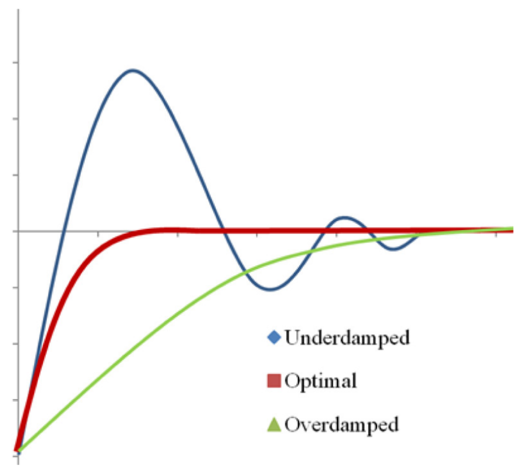

Figure 5. Desired force output response.

3.2. PID Controller

PID control is a widely used control method to create feedback mechanisms that correct for error between the desired input and obtained output. It consists of three terms: the proportional term (P) -which is a multiple of the current value; the integral term (I) -consisting of a multiple of the value of the error accumulated over time; and the derivative term (D) -which is a multiple of the rate of change of the error [5]. In this study, the derivative term was not utilised as it may generate instabilities in the response, thus the system would not reach a steady-state [6]. The P and I terms will be collected into a single controller and introduced into the negative feedback loop as C_r shown in Figure 4.

The PI controller is expected to respond appropriately around the tuned parameters, but if the system experiences disturbances that are significantly different the PI controller will not perform optimally [7]. In addition, the PI controller does not take into account uncertainties, such as non-linearities and error in the plant model, therefore restricting its robustness [8]. In this study, the PI controller has been tuned to a step change from a desired output of 0 to 80N using the integrated tuning algorithm in the Simulink software. The terms obtained to produce the desired response (i.e. no overshoot) were: P=1.2 and I=34.

3.3. H∞ Controller

3.3.1. Introduction

The H∞ control algorithm was created as a feedback system during the development of Quantitative Feedback Design Theory by Isaac Horowitz. It is designed to maintain the desired system response and error signals within a predetermined tolerance while overcoming uncertainty effects in the whole system [9]. The H∞ controller is inherently more robust in unstable conditions as it automatically seeks out previous or new stable values to recover, instead of varying continuously at a certain speed [10]. The mathematics behind the derivation of the H∞ controller are relatively complex, although software such as MATLAB, automatically performs the necessary iterations to construct an optimum stable controller.

The overall design of the controller is concerned with shaping the loop gain,$C(s)P(s)$, for the controller,$C(s)$, and the plant, $P(s)$ to make the sensitivity function,$S(s)$, control sensitivity function, $R(s)$, and complementary sensitivity function, $T(s)$, as small as possible for the system. The definitions of the function are [11]:

$$S(s) = [I + C(s)P(s)]^{-1} \tag{3}$$

$$R(s) = C(s)[I + C(s)P(s)]^{-1} \tag{4}$$

$$T(s) = C(s)P(s)[I + C(s)P(s)]^{-1} \tag{5}$$

It is not possible to make all of these sensitivity functions small in the same frequencies bands, therefore an augmented plant must be created utilising transfer functions to act as weightings [12]. These consist of three functions: The sensitivity weighting, W_s; the control sensitivity weighting, W_u; and the complementary sensitivity weighting, W. Each weighting is derived manually and serve different purposes to control the overall system in a predetermined manner by increasing or decreasing the responsiveness at certain frequencies. The weightings act on the following sensitivity functions are:

$$W_S(j\omega)S(j\omega) \tag{6}$$

$$W_U(j\omega)R(j\omega) \tag{7}$$

$$W_T(j\omega)T(j\omega) \tag{8}$$

A stable *H∞* controller is then developed by ensuring the H∞-norm (maximal possible amplification) of the cost function, abides by the condition:

$$\left\| \begin{bmatrix} W_S(j\omega) & S(j\omega) \\ W_U(j\omega) & R(j\omega) \\ W_T(j\omega) & T(j\omega) \end{bmatrix} \right\|_\infty \leq \gamma < 1 \tag{9}$$

A further constraint to the weighting function is:

$$W_S{}^{-1}(j\omega) + W_T{}^{-1}(j\omega) >> 1\forall\omega \tag{10}$$

at each frequency [11]. The shaping of the weightings was performed in accordance to the procedures outlined in [9].

3.3.2. Defining the H∞ controller

To obtain the Bode plot of the plant model's frequency response, the Simulink model must be linearized. This linearization process is performed on Simulink by setting linear analysis points, including an Input perturbation at the desired force input and an Output measurement on the output force. This results in a linearized state-space model in the general are:

$$\dot{x} = Apx + Bpu \tag{11}$$

$$y = Cpx + Dpu \tag{12}$$

The selection of the weightings is the most important step as they directly define the response of the controller and its stability. An example of the effect of the weightings is shown in Figure 6 where it is possible to see that the quickest response is from the high sensitivity weighting, W_s, transfer function. However, this causes the controller to become too sensitive to error and thus leads to either overshoot, or in this case, instability as the controller attempts to continuously correct itself at the steady-state. If the sensitivity weighting is too low, the response of the controller and the system itself is reduced and therefore an optimum stable level in between the two must be derived.

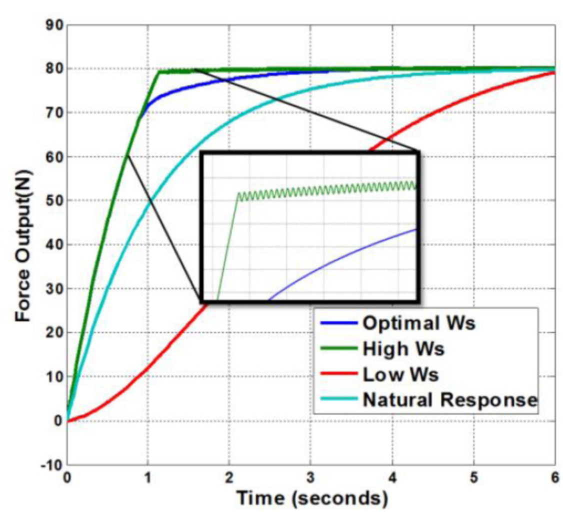

Figure 6. Force output response with different sensitivity functions.

The optimisation of the weighting values was performed, through methods given in [9], to obtain a stable configuration with desired performance, Figure 6. The most effective technique was to derive and optimise a controller solely with the sensitivity weighting and then proceed to add the remaining two to obtain a more robust system. In this study the H∞ controller was tuned to a step input of 0-80N which was the same condition applied to the tuning of the PI controller. The transfer functions selected for the three weightings are then:

$$W_S = 85 \times \frac{87S + 0.07}{0.0011s^2 + 1.5s} \quad (13)$$

$$W_u = 1.01 \times \frac{0.5s + 0.025}{0.05s + 0.025} \quad (14)$$

$$W_T = \frac{1s + 1}{1s + 900} \quad (15)$$

The magnitudes of the optimal weighting functions selected, as well as the plant models frequency response, are shown in Figure 7.

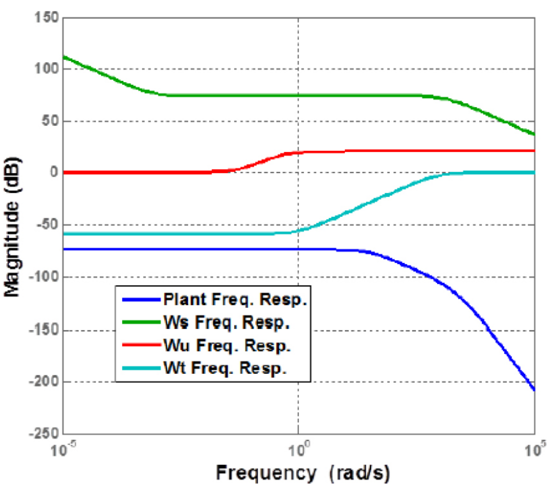

Figure 7. Bode plot of magnitude of weightings/plant model.

Once the plant model and weightings are created, an augmented plant is generated in Matlab, and from that the full H∞ controller derived. The controller is returned to state-space form, ready to be implemented in a closed negative feedback system.

4. CONTROLLER SIMULATION RESULTS

To compare the response of the PI and H∞ controllers, different situations were implemented to push the controllers to extremes that would potentially be experienced during actual system operation. Throughout the results section, the proportional and integral terms for the PI controller and the weightings for the H∞ controller have not been modified. The work here therefore presents the closed loop response due to tuning the controllers for a specific response and placing them under different operating conditions without further tuning. As mentioned before, the two controllers were tuned for an initial step input of 0 to 80N and the output force responses for both controllers can be seen in Figure 8. It is clear that the H∞ controller has a quicker initial response in comparison to the PI controller, and they both achieve the same steady state response. Both controllers achieve the desired force response without overshooting while responding quicker than the natural response. This shows that the overall system has benefitted from the introduction of a control feedback system as changes in desired force can be controlled closely and quickly. This has value if the cause of defects is related to a sudden change in load.

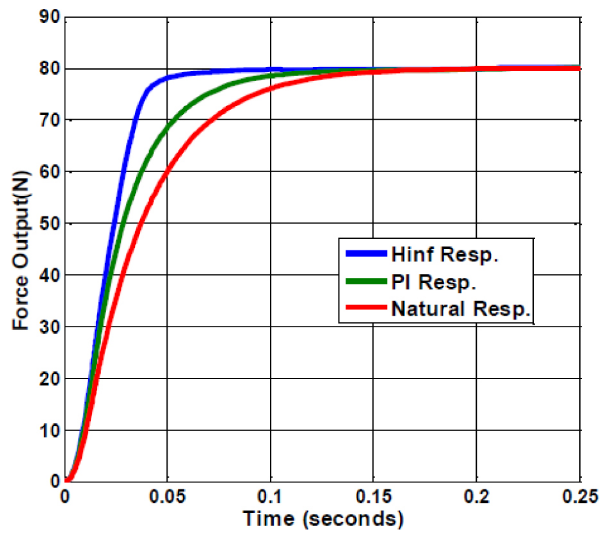

Figure 8. Force output comparing H∞ and PI controllers

4.1. Step-Change of Desired Output Force

Simulations were run to determine the response of the system to different step changes in desired force value. This simulates situations where the user requires applying different magnitudes of forces at different locations. For example, differences in cross-section thickness of the composite material, or specific features that may require variable force control. The results for a positive small step (20N), a positive larger step (60N) and a negative medium step (30N) are presented in Figure 9 for both controllers. Results show that the H∞ controller responds quicker than the PI controller, although with smaller steps, the difference is less noticeable. It is again visible how control implementation benefits the overall functionality of the system as the natural response is considerably slower at following the desired force output.

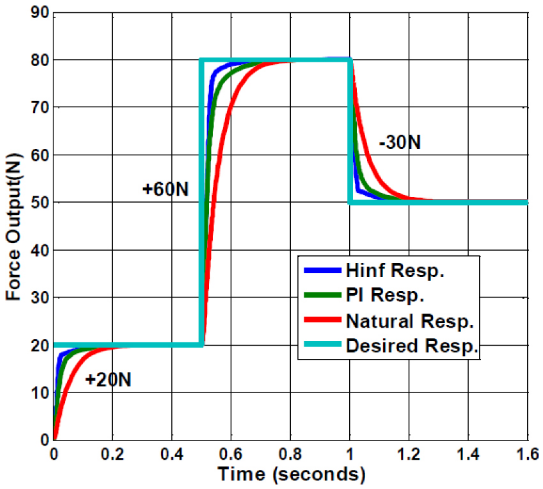

Figure 9. Force output response due to varying the desired force to 20N, 80N and 50N in turn

4.2. Step-Change Disturbance Input

In this simulation a reactive force step input is instantaneously applied to the output of the cylinder. This represents a sudden rise/drop in the composite geometry resulting in a reactive positive/negative force respectively. This could be due to the associated stiffness of the composite material's surface, or sudden changes in the tooling or process along the mould surface. The results shown in Figure 10 present an alternate finding to the previous simulation. In this case it could be viewed that the current feedback based control system would not be beneficial to the prevention of wrinkle formation. This is because the two controllers respond over-aggressively to the force input, causing a force overshoot as a response when returning to the desired position, while the natural response gently reaches a steady-state. This overshoot could potentially form defects in the laminate and therefore both controllers would need to be returned to better eliminate disturbances. In the case of the H∞ controller the control sensitivity weighting, W_U, would have to be increased to limit the maximum response force. Alternatively, the sensitivity function could be reduced to make the controller less sensitive, although this would have the consequence of making it slower to respond to step changes found in Section 4.1. Comparing the two control methods there is little difference in the response times for the different magnitudes of the step-inputs. However, the H∞ controller produces less of an overshoot and therefore could be considered slightly better. The amount of overshoot is also proportional to the magnitude of the step input.

4.3. Sinusoidal Desired Output Force

A sinusoidal wave was introduced as the desired output force of the cylinder, simulating situations where the user may vary the desired output constantly in a smoother manner. This would potentially apply to curved surfaces with varying cross-sectional thicknesses requiring a smoother force transition. The simulation was performed utilizing various frequencies, however, it was found that the controller's response would only deter from the desired response at relatively high frequencies. The frequency selected to present this deviation is shown in Figure 11 for a frequency of 1.3Hz and amplitude 50N. The figure shows that both controllers struggle to follow the desired response, although, the H∞ is more in phase when compared to the PI controller. To improve on the response of both controllers, their sensitivity would have to be increased by increasing their terms/weightings, although this could potentially lead to an overshoot in the output for other situations.

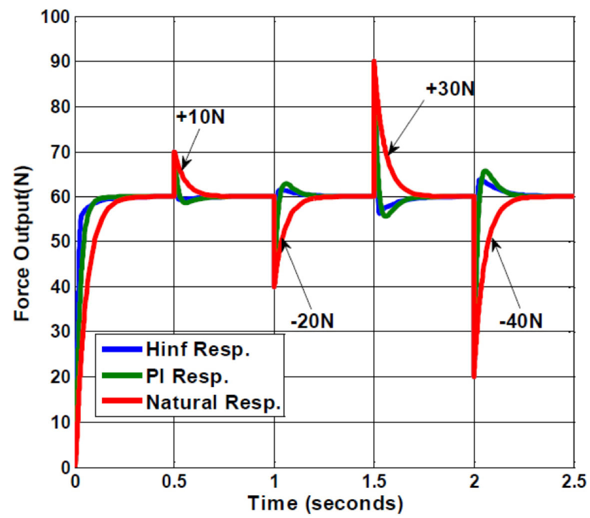

Figure 10. Force output response due to a step disturbance input of varying magnitude from a 60N constant

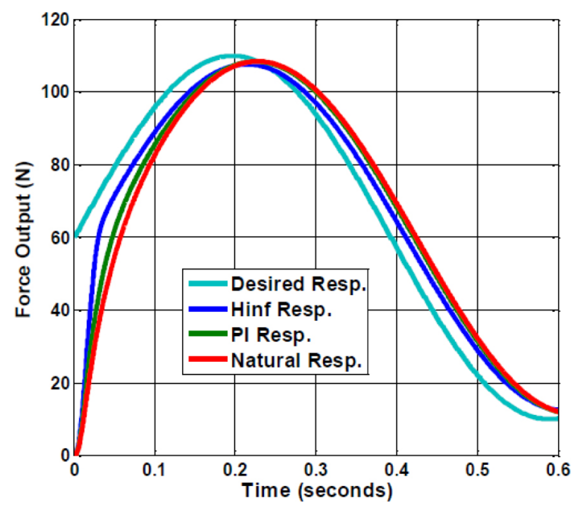

Figure 11. Force output response due to sinusoidal variations of 1.3Hz and 50N amplitude in desired force

4.4. Sinusoidal Disturbance Input

This simulation shows the response of the two controllers when a sinusoidal disturbance force is input as a reaction to the output force from the cylinder. This is similar to the step input in that it simulates the reaction due to the change in mould geometry and any gradual resistance from the composite materials. The sine wave simulates a regular varying surface with a wavy texture that is equal to the frequency and amplitude of the input. In Figure 12 the results for a low frequency/low amplitude surface (0.8Hz, Amp.20N) are shown as well as for a high frequency/high amplitude surface (2.4Hz Amp.

40N). The low frequency and amplitude surface presents vary little deviation in the controllers' response in comparison to the natural response due to the disturbance. This presents the importance of having a control feedback loop in the overall system as the output force would largely fluctuate with the geometry of the surface without one. In the case of the geometry with the high frequency and amplitude, in comparison to the PI controller, the H∞ controller has a better response as there is less deviation in terms of amplitude from the desired 60N.The improved robustness of the H∞ controller over the PI controller, is therefore highlighted in this scenario.

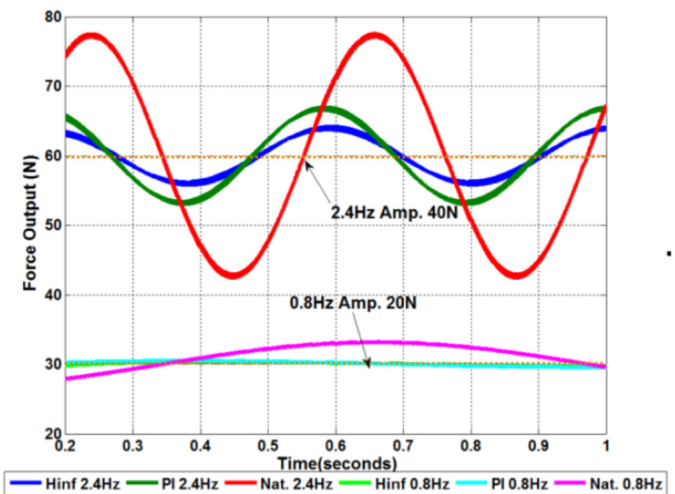

Figure 12. Force output responses to a sinusoidal disturbance input of a high frequency wave, 2.4Hz/ amplitude 40N at 60N, and a low frequency wave 0.8Hz/ amplitude 20N at 30N

5. DISCUSSION OF RESULTS

With the exception of the step input disturbances, the other three simulations performed stress the importance of having a control feedback system. The use of the controllers ensures a quicker response to changes in desired force output and less output deviation due to disturbances than are found naturally in the system. To resolve the overshoot issue presented with the step input disturbance tests, the terms/weightings of the controllers would have to be modified to reduce their sensitivity. It is therefore the final user's decision on whether the controller is preferred to respond more appropriately to sudden step changes or constantly varying disturbances, which will ultimately depend on the geometries of the manufactured composite parts. In most cases the forming speeds used are in the mm/s range, as such the most important criteria will be the application of a constant and regulated force.

With respect to the comparison between the PI controller and the H∞ controller, it is clear that the H∞ is more robust, responds quicker and generally has a greater accuracy. The shape of the response can be far more controlled in terms of selecting the sensitivity of the controller at different points/frequencies by implementing the weightings. These results support previous observations utilizing H∞ control made by D.T.Branson III, 2006 [9], L.Lin [13] and N.Xiros [14], where they all conclude that the H∞ controller is far more stable and achieves a greater accuracy of the desired response to that of the PI controller.

Limitations in the robustness of the PI controller become apparent at the extremes of the operating ranges when utilising higher frequencies or larger step changes in desired force profiles. The advantage of the increased robustness of the H∞ controller will be beneficial for high frequency changes in desired force output and/or if the speed of the rolling process is increased for geometries with large surface variations. The use of controllers, such as H∞, may also allow for relatively fast reactionary measures to be applied to correct/prevent defects forming as they are detected during forming operations.

6. CONCLUSIONS

Results obtained through simulation show that the H∞ controller responds quicker and more robustly in comparison to the PI controller. The PI controller is limited in responding to situations that are far from its tuning scenario becomes more visible at higher frequency/amplitude disturbances.

In conclusion, the derived controllers clearly benefit the composite forming process as they create a closed feedback system with greater control on the magnitude and timing of the output force. Within the next phase of research H∞ control will be incorporated into the current forming test cell, and applied over a full forming example to further evaluate the effectiveness of this controller on the force parameter.

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