

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 Mathworks [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:

$$P_i = F_o A \quad (1)$$

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:

$$F_R = Lk \quad (2)$$

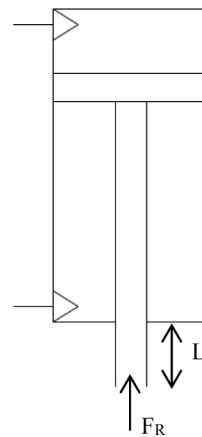


Figure 1. Free body diagram of actuator and reactive force.

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.

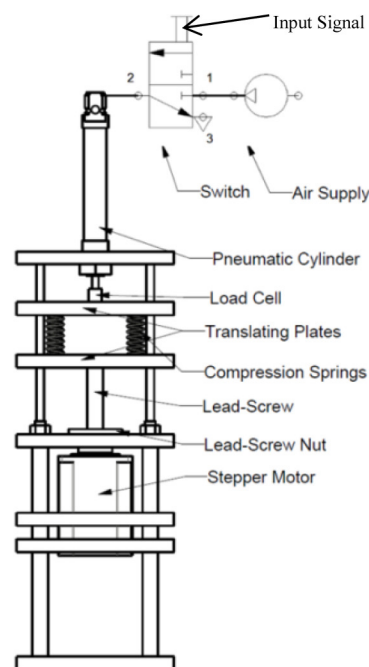


Figure 2. Physical test cell schematic

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 $\pm 10\text{g}$ 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:

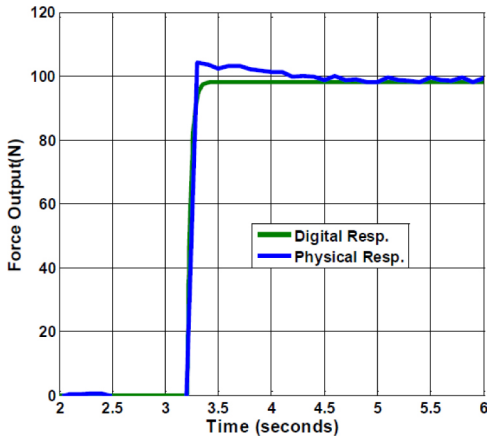


Figure 3. Comparison of digital and physical pressure application and response

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.

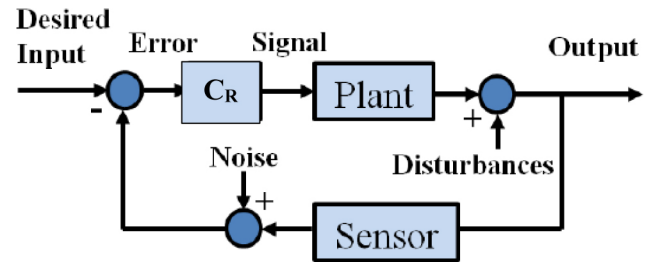


Figure 4. General control block diagram for the system

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:

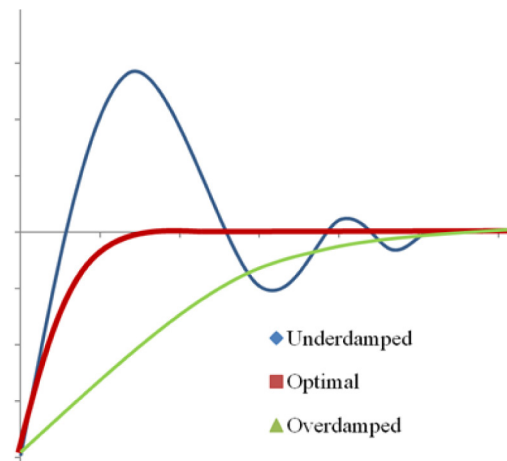


Figure 5. Desired force output response.

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