DESIGN OF A FORCE FEEDBACK CONTROLLER FOR A PNEUMATIC GLUING STATION BY EMPLOYING FEM SIMULATIONS

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Abstract: In the automotive industry, acoustical materials play an essential role in the reduction of rolling noise levels. Such insulators are bonded to exposed cavities by means of adhesives. The gluing process benefits from the wide scale use of pneumatic actuators. One essential aspect of the underlying air drives is the dynamic control of the actuating force. The present paper proposes a new approach for deriving the transfer function of the plant by employing transient structural simulations. A numerical computing environment is further use to decide and tune a closed-loop controller.

Keywords: feedback, pneumatics, gluing, finite element method, control

1. INTRODUCTION

In the past decades, manufacturers of passenger and commercial vehicles are facing increasing design challenges due to the emerging pass-by noise regulations [1]. In this regard, the UN/ECE R51.03 defined emission reductions with limits of 72 dB in 2016 [2]. To meet such requirements, acoustic materials are employed in the development of automotive components for reducing the side effects of forced vibrations [3]. One limiting aspect of the aforementioned solutions is governed by the extended assembly cycle times, especially when the insulators are bonded directly to the exposed cavities [3]. A typical working cycle of a gluing station comprises four distinct stages [4]: the secure location of the workpiece, dispensing of the glue, handling of the acoustical material and the exertion of pressure for facilitating the uniform spreading and solidification of the adhesive layer. To enhance the process, stakeholders have made effective use of robotic cells [5]. From this perspective, the material handling, glue dispensing and squeezing cycles can be partly or fully

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automated with the support of actuating systems [6]. In this regard, pneumatic air drives are one of the most popular choices [7]. This is due to the fact that the gluing process is fast-moving, demands low output forces and coarse positioning accuracy. Even so, pneumatic actuators require an adequate force feedback control methodology for maintaining a constant contact pressure [8]. The problem becomes even more complex due to the non-linear behavior of the porous or hyperelastic materials employed [9]. To overcome such issues, the present paper proposes a new approach for evaluating the dynamic behavior of the plant with the support of transient structural analysis based on the Finite Element Method (FEM). At first, a simplified simulation model is developed comprising the insulating material and the part subjected to the treatment process. Imprints of the moving elements are performed to materialize the junction areas. A step load is considered for evaluating the output contact pressure. In the next stage, the system identification toolbox from MATLAB is employed for deriving a transfer function from the simulation data. The representation of the process is transferred to the Simulink environment for deciding an optimal control strategy. The given concepts are proved by means of a practical study.

2. THE DESCRIPTION OF THE STUDIED GLUING STATION

The studied gluing station is illustrated in figure 1.

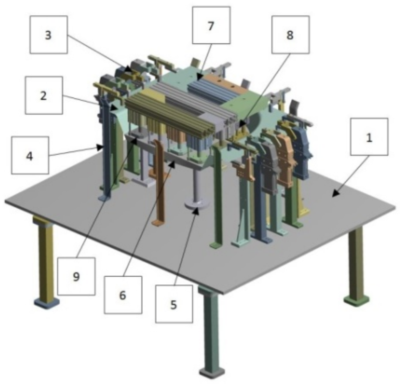


Fig.1 Isometric view of the main components of the studied gluing station

The solution comprises a working table (1) that is employed to configure the stationary and air-driven modules required to restrain all the degrees of freedom of a sheet metal workpiece (2). This objective is completed with the support of pneumatic power clamps (3) and standalone columns that are used for locating the part in radial (4) and axial directions (5). Adhesive spots are applied in prescribed locations found at the junction between the workpiece and the acoustical material (6). A human operator or an industrial manipulator carries out the handling of the parts. The spreading and solidification of the adhesive layer is ensured by means of an end-effector (7) that is equipped with an array of compact double-acting pneumatic cylinders (8). Rubber cushioning (9) is provided at the bottom of the rods to enhance the contact pressure.

Figure 2 depicts the pneumatic diagram required to control the force and velocity of the air-driven actuators.

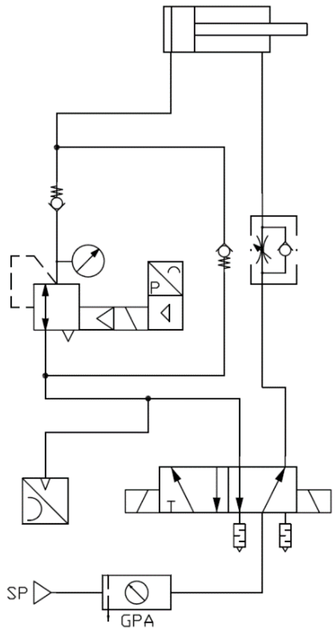


Fig.2 Pneumatic diagram for the velocity and force control of a single cylinder

Compressed air is feed to the system by means of a 7 bar supply source. The working agent is filtered, lubricated and its pressure is adjusted with the support of a preparation unit. A 5/2 solenoid directional valve is employed to power groups of double-acting pneumatic cylinders. In the operating positions, the air flows from the pressure to the actuator ports. A proportional pressure regulator is included to dynamically adjust the operational parameters of the pneumatic cylinder in the positive movement end-position. Two analogue pressure sensors are used to confirm the set point value. A one-way flow control valve is included to limit the velocity of the pneumatic cylinder in the negative movement end-position. Thus, the sticking between the cushioning of the piston rod and the acoustical material is avoided. Spring loaded check valves are employed to constrain the flow in the exhaust stage of the cylinder.

The minimum operational requirements of the pneumatic cylinders are identified based on sizing methodology depicted in [10]. In this regard, the actual force of one cylinder can be derived from:

$$F = p_a \cdot S \geq F_m + F_f + F_i \tag{1}$$

Where: F represents the force exerted by the piston rod [N], p_a the supply pressure [MPa], S the cross-section area of the piston [mm^2], F_m the required force [N], F_f the frictional force [N] and F_i the inertial force [N].

The effects of the resistive loads are taken into account in the sizing stage by means of a coefficient k = 1.2 …. 1.5, that is decided based on the velocity of the piston rod:

$$F_u = k \cdot F_m \tag{2}$$

The section area S_1 [mm^2] of the piston for a double acting pneumatic cylinder can be calculated as:

$$S_1 = \frac{\pi \cdot \left(D^2 - d^2\right)}{4} \tag{3}$$

Where: D and d represent the piston and rod diameters [mm].

Based on relationships (1-3) the diameter of the cylinder D_c [mm] can be derived as:

$$D_c = \frac{4 \cdot F_u}{\pi \cdot p_a} \tag{4}$$

The rod thickness coefficient is taken into account for identifying the optimal diameter of the piston rod:

$$\phi = \frac{D^2}{D^2 - d^2} \tag{5}$$

Based on 5, the diameter of the piston rod d [mm] can be calculated as:

$$d = D \cdot \sqrt{\frac{\phi - 1}{\phi}} \tag{6}$$

The air consumption of the pneumatic cylinder for a 1 cm positive stroke can be identified as:

$$q_a = \frac{p}{p_0} \cdot \frac{\pi}{4} \cdot D^2 \cdot 10^{-5} \tag{7}$$

Where: p represents the absolute pressure at the input of the cylinder [bar] and p_0 a pressure coefficient of 1.013 [bar].

The air consumption of the pneumatic cylinder for a 1 cm negative stroke can be identified as:

$$q_r = \frac{p}{p_0} \cdot \frac{\pi}{4} \cdot \left(D^2 - d^2\right) \cdot 10^{-5} \tag{8}$$

Thus, the air consumption of the pneumatic cylinder for a complete cycle can be deprived as:

$$q = \left(q_a + q_r\right) \cdot c \tag{9}$$

Where: c represents the stroke [cm].

From 9, the air flow requirements of a pneumatic cylinder can be identified as:

$$Q = q \cdot n \tag{10}$$

Where: Q represents the air flow [l/min].

Table 1 represents the results achieved, based on the methodology depicted above.

Table 1 **Minimum requirements of the pneumatic cylinder**

Parameter	Value	Unit	Comments
F_m	250	N	Defined by the most critical squeezing force
c	82	mm	Maximum stroke in the positive movement end-position
n	20	cycles/min	Maximum number of cycles / minute
p	7	bar	From the pressure source
D	12	mm	Minimum diameter of the cylinder, in accordance with UNI ISO 3320
d	6	mm	Minimum diameter of the piston rod, in accordance with UNI ISO 3320
Q	16.38	Nl/min	Minimum air flow requirements

3. THE DEVELOPMENT OF THE SIMULATION MODEL

The development and tuning of a control methodology requires in the first stage the definition of mathematical expression that describes the relationship between the input and the output of the plant. One approach is to evaluate the dynamic behavior of the system under a step load by experimental means. The results can be used to identify an s-domain transfer function with the support of the statistical methods of system identification procedures [11].

A transient structural simulation model is developed to overcome the resource requirements of physical experiments [12]. The model consists of a 3D representation of the acoustical material. Imprints are performed to materialize the piston rod cushioning – insulator interaction area (Fig.2).

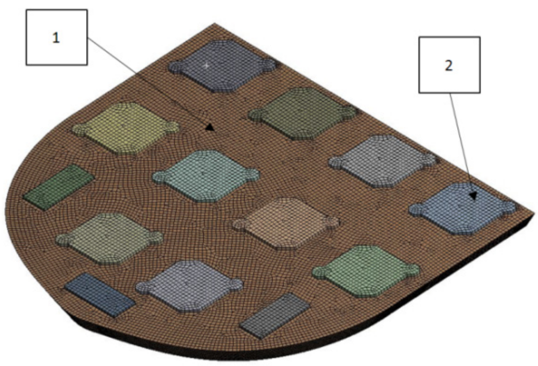


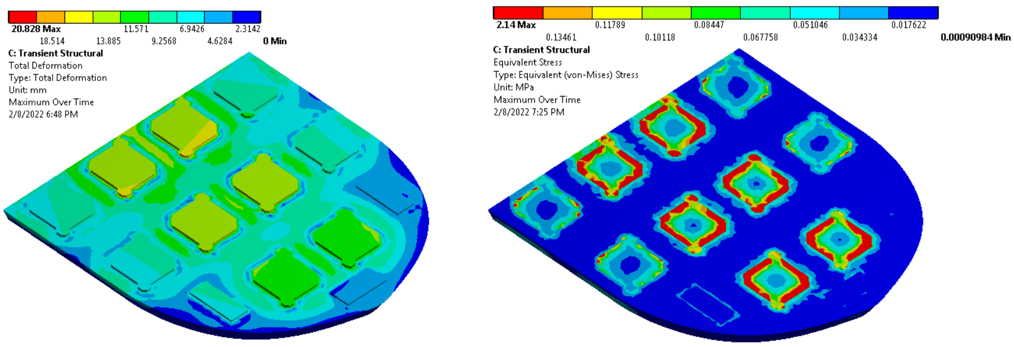
Fig.2 Simplified representation of insulator (1) and the piston-rod cushioning interaction area

ANSYS Workbench interface is used for developing the FEM model [13]. The material used is a COR12V Cork thermoset elastomer. Its characteristics are defined based on uniaxial, biaxial, shear stress-strain curves. Volumetric test data is included as volume ratio vs. hydrostatic pressure. The non-linear stress-strain behavior is modeled by including a Neo-Hookean hyperplastic material model definition.

The rubber cushioning employed at piston rod ends is kept in the simulation model for all pneumatic cylinders. Contact elements are defined to capture the frictional interaction between the bodies. The result of interest is the time vs. contact pressure.

In the next stage, the maximum force developed by each pneumatic cylinder is applied as a step pressure that is acting on the cushioning of each piston rod.

Figure 3 – a and b depicts the maximum over time total deformation [mm] and equivalent von-Mises stress [MPa] occurring at the level of the insulator material.



(a) (b)

Fig.3 Maximum over time total deformation (mm) and von-Mises Stress of the insulator

4. FORCE-FEEDBACK CONTROL

The contact pressure vs. time curve derived from the transient structural analysis is employed for identifying a transfer function that fits the output of the model with a low margin of error. MATLAB System Identification toolbox is used for this purpose.

A 2 pole and 1 zero transfer function was estimated with 99% accuracy, having a final prediction error of $5.34 \cdot 10^{-7}$ and a mean squared error of $3.92 \cdot 10^{-7}$. The parameters of the function are presented in equation 9:

$$G(s) = \frac{0.0001 \cdot s + 0.000173}{s^2 + 0.4788 \cdot s + 0.168} \tag{11}$$

In the next stage, the step response of the system is compared with the results derived from the transient analysis. A good match can be noticed between the two curves (Fig.4).

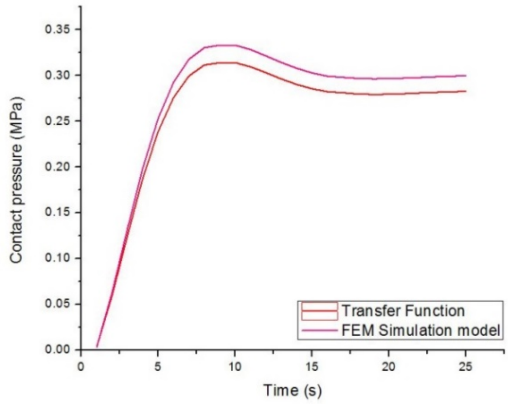


Fig.4 Step response of the system achieved by the transfer function and FEM Simulation model

The contact pressure gain error between the output of the estimated transfer function and the FEM simulation model is 3.84% and the settling time error is 5.83%.

In the last stage, the MATLAB Simulink environment is employed for developing and tuning a closed-loop PID controller [14]. A transport delay of 0.5 seconds is included based on the response of the differential proportional pressure regulator from the physical system. The saturation limits are defined by considering the maximum operating force of the pneumatic cylinders. Tuning of the controller gains is completed by using the model-based procedure.

Figure 5 depicts the step response of the system after tuning.

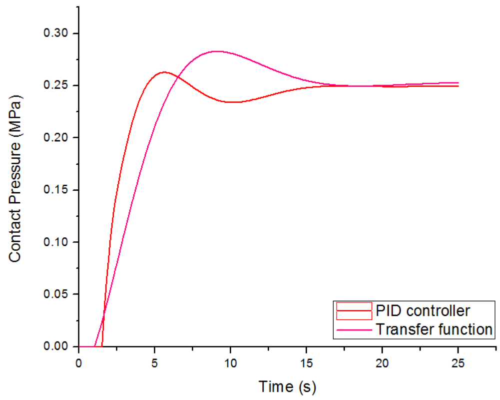


Fig.5 Step response of the system achieved by the open-loop transfer function and the PID controller

5. CONCLUSIONS

The present paper addresses the issues of force feedback control in pneumatic gluing stations. A FEM simulation model is employed for evaluating the step response of the system. The resulting contact pressure vs. time graph is used for identifying an s-domain transfer function of the process based on system identification procedures. Numerical computing environments can be used from this stage to design and tune various control strategies. The approach can be employed for scheduling the actuating signal of proportional pressure regulators or for prototyping a digital controllers.

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