Master's Thesis Engineering Technology

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Expansion of an Automated Injection Molding Production Cell via Non-Destructive Stiffness-Based Quality Control

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Introduction

Context

This research is conducted at the **Polymer Processing & Engineering** (PPE) research group at **KU Leuven**. It is part of a project on product traceability in automated injection molding. The primary goal is to correlate the properties of injection molded parts with the input parameters of the process using in-line monitoring, enabling smarter and more efficient Industry 4.0 production.

Problem statement

In the industry, part quality is currently assessed mainly through **offline sampling**, which is time consuming, mostly destructive, and not fully representative. This approach delays feedback and risks overlooking defective parts or trends during production. As a result, there is growing interest in **real-time, in-line monitoring methods**.

Objectives

The **primary objective** of this thesis is to develop and implement an in-line, non-destructive system to evaluate the **relative stiffness** of injection molded parts during production and link the results to production data. The system must be **fast**, **reproducible**, and operate within the **physical** and **timing constraints** of the automated injection molding cell. It should also integrate with the existing **robot arm** and **traceability** platform to support real-time quality monitoring. This enables early detection of quality deviations and facilitates data-driven process adjustments.

Literature study

In-line Quality Control in Injection Molding

In-line quality control techniques in injection molding range from **geometric** and **visual inspection** using OCMMs for dimensional accuracy to **sensor-based monitoring** that captures in-mold parameters such as **pressure** and **temperature** to infer properties like **stiffness** and **tensile strength**. Emerging **machine learning** approaches allow real-time classification of part quality using process data.

Non-Destructive Stiffness Testing Methods

3-point bending: determines a material's flexural stiffness by measuring its resistance to bending when loaded at the midpoint between two supports.

Figure 1: ASTM D790 standardized flexural test [1]

Ultrasonic testing: estimates stiffness by measuring the velocity of high-frequency sound waves through a material, with the wave speed being directly related to its elastic modulus.

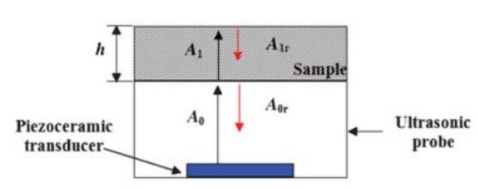


Figure 2: Ultrasonic wave travel for pulse echo mode [2]

Impulse Excitation (RFDA): determines the stiffness of a material by analyzing its natural resonance frequencies after a mechanical impulse is applied to a sample with known geometry and mass.

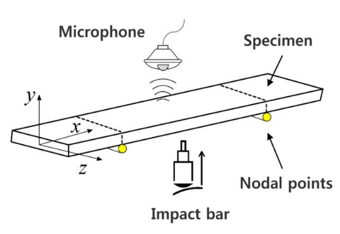


Figure 3: RDFA measurement principle [3]

Experimental setup and testing

Design of Experiments

To evaluate these methods, a **DoE** was used to create controlled **batch variations** of 90 injection-molded samples from 8 process variants, enabling **systematic evaluation** of each testing method's **sensitivity** and **discrimination ability** to detect relative stiffness differences. Figures 6, 8 and 11 compare the relative values normalised to their respective maximum. (note: the y-axis scale is broader only for Figure 6 for visual purposes)

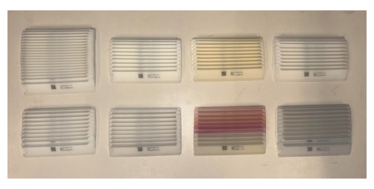


Figure 4: Sample selection across 8

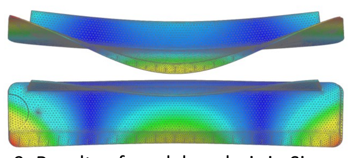


Figure 9: Results of modal analysis in Siemens NX

Experimental setup

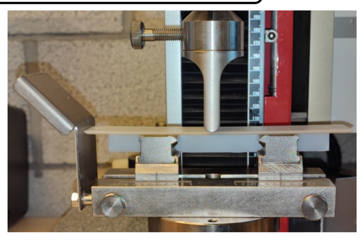


Figure 5: ZwickiLine BZ2.5/TS1S Bending test machine

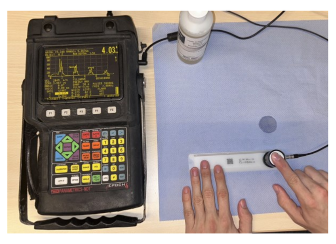


Figure 7: Ultrasonic test setup

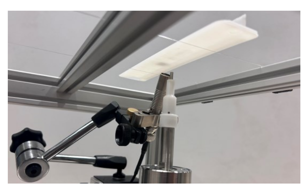


Figure 10: RFDA Essential

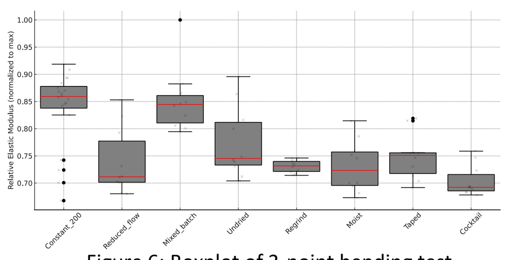


Figure 6: Boxplot of 3-point bending test

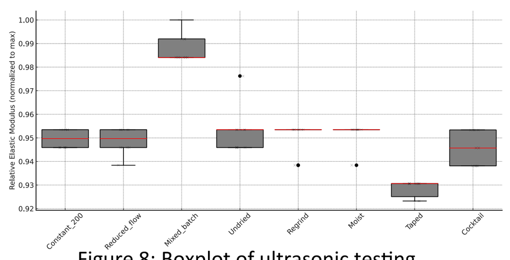


Figure 8: Boxplot of ultrasonic testing

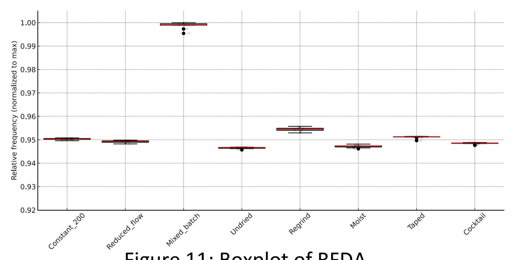


Figure 11: Boxplot of RFDA

Based on both experimental results and theoretical comparison, RFDA was selected as the most reliable and sensitive method.

Design constraints

Thermal influence on frequency behavior

Freshly molded ABS parts remain warm and in a softened amorphous state post-ejection, which affects their **natural frequency** and **stiffness**. RFDA tests were conducted on ten samples immediately after molding, with continuous logging of **temperature** and **frequency** to confirm a temperature-dependent vibrational response. These findings highlight the importance of **sufficient cooling** prior to RFDA testing to ensure reliable quality control.

Forced cooling and buffer optimization

Applying **forced cooling** consistently **halved** the overall cooling duration from approximately 10 minutes to 5 minutes, shown in Figure 12. Fan orientation had minimal impact on cooling time. RFDA tests on ten forced-cooled ABS samples confirmed a **strong linear correlation** between temperature and natural frequency (R^2 = 0.97), as shown in Figure 14. To support a 30-second injection molding cycle time and 5-minute cooling period, a buffer holding 10 pairs of samples enables continuous, consistent testing.

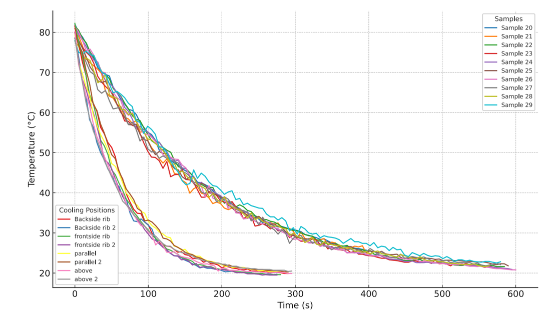


Figure 12: Air cooling vs forced cooling

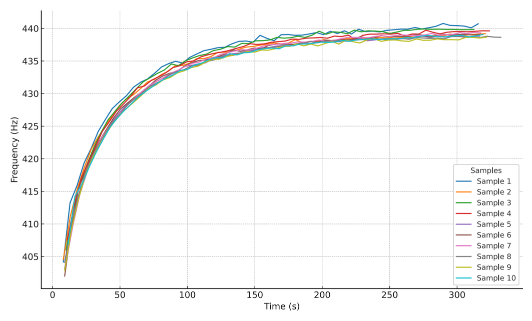


Figure 13: Time-dependent frequency behavior of freshly molded parts

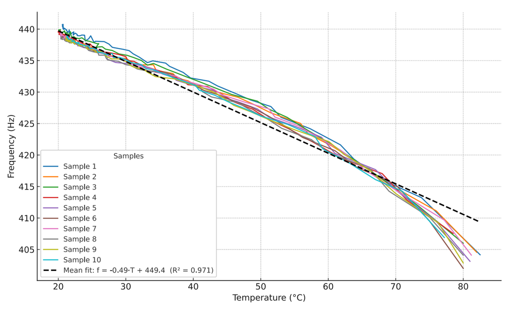


Figure 14: Linear regression of frequency vs temperature of freshly molded parts

CAD Design

Conceptual design proposals

Several buffer concepts were evaluated, and the **linear buffer** was chosen for its simplicity and ease of integration within the limited space of the injection molding cell. The **3-axis robot** places freshly molded parts upside down into the buffer, which is positioned within its working range. In a future upgrade, a **6-axis robot** will be added to retrieve cooled samples from below the buffer and place them upright on the **RFDA station**, enabling continuous and automated testing. The buffer design allows bottom-side pickup without obstructing robot movement, while the overall layout avoids interference with existing equipment and ensures safe operation.

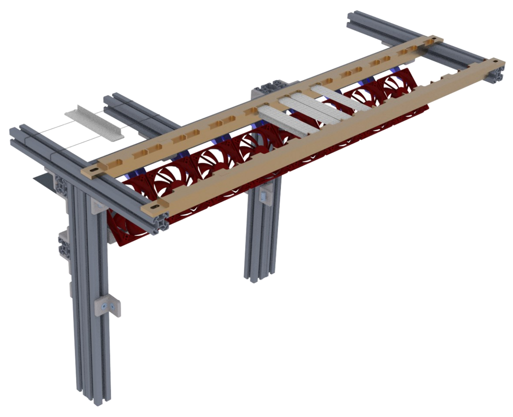


Figure 15: CAD design render with PTC Creo

Implementation with cell

The setup was built using standard **extrusion profiles** and assembled with T-slot bolts for modularity and easy adjustment. The buffer consists of two symmetrical laser cut assemblies, which has a modular top layer for future product changes. A fixed mounting plate for the exciter and microphone allows for RFDA measurements.

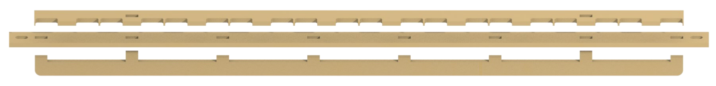


Figure 16: Exploded view of the three laser cut parts for buffer

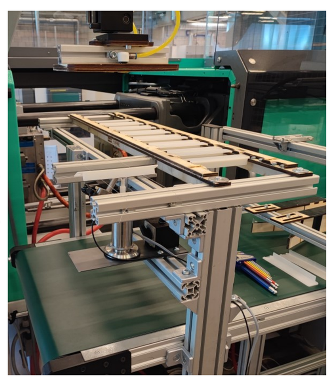


Figure 17: Implementation in the cell

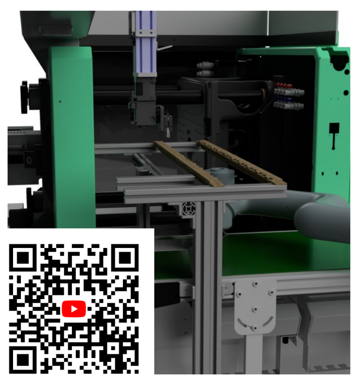
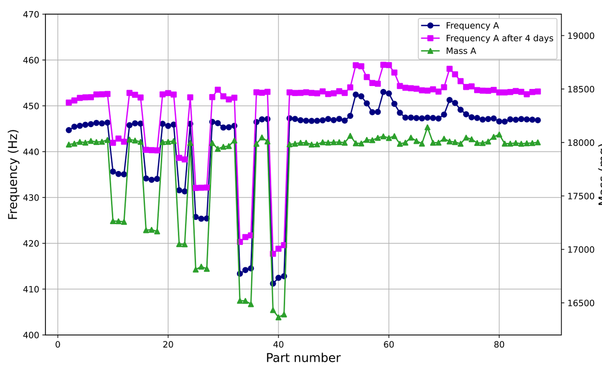


Figure 18: Render of full CAD assembly

Results and discussion

Results

Two process deviations were tested: **incomplete mold filling** and **material impurities**. Lowering the packing pressure caused a **gradual drop** in **resonant frequency**, linked to reduced stiffness. Adding a different ABS polymer caused **frequency peaks**, confirming the system can detect subtle material variations even when mass and appearance remain mostly unchanged.



Figuur19: Frequency during a production series and after 4 days together with mass of all samples A

Conclusion

This master's thesis developed and validated a **non-destructive**, **stiffness-based quality control system** for injection molding. Among several evaluated methods, **RFDA** was chosen as the most suitable due to its sensitivity, speed, and ease of automation. A custom buffer system was integrated for automated part handling and forced cooling. Validation tests confirmed the system's ability to detect both incomplete filling and material impurities, proving its added value for in line quality monitoring.

Future work

Future work includes **full automation** with robotic handling, monitoring of **other mechanical properties/materials**, real-time **data integration**, investigating **startup effects**, and defining the **detection limit** for contamination.

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[1] ASTM Standard D790-17, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, *ASTM International*, West Conshohocken, PA, 2017.

[2] F. Lionetto and A. Maffezzoli, "Polymer characterization by ultrasonic wave propagation," *Advances in Polymer Technology*, vol. 27, no. 2, pp. 63–73, 2008.

[3] J. Wang, X. Wang, and H. H. Ruan, "On the mechanical β relaxation in glass and its relation to the double-peak phenomenon in impulse excited vibration at high temperatures," *Journal of Non-Crystalline Solids*, vol. 533, 4 2020.

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