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Original Research

MODULAR TECHNOLOGICAL LINE FOR ASSEMBLING AND TESTING CAR DAMPERS

MODUŁOWA LINIA TECHNOLOGICZNA DO MONTAŻU I TESTOWANIA AMORTYZATORÓW SAMOCHODOWYCH

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Abstract

Suspension systems are integral for a safe and comfortable driving experience, with dampers as crucial components. The global car dampers market is expected to grow due to the increasing demand regardless of the type of cars drive technologies. Manufacturers are focused on innovating both damper design and production processes, aiming for better energy and material efficiency. Product analysis, line layout, and quality control are essential components of the damper assembly and testing process, ensuring that finished components are of high quality and meet market demands. Proper dampers assembly line design is essential for efficient mass production, requiring meticulous planning of products, processes, and line layout. Methodologies like concurrent engineering aid in addressing design challenges efficiently, fostering innovations and collaboration among designers, engineers, and decision-makers. The purpose of project described in this study was to develop an modular assembly line for dampers integrating innovative features for efficiency, including high measurement accuracy in functional testing, automation, and cycle time reduction, meeting the diverse needs of OEMs and Tier1 companies worldwide. This project received funding form Smart Growth Operational Program 2014-2020 under designation POIR.01.01.
01-00-1029/17-00. The line has been developed, tested and implemented and this study focuses on the description of the individual line modules.

Keywords: dampers, dampers assembly lines, concurrent engineering, assembly line designing

Streszczenie

Układy zawieszenia są warunkiem bezpiecznej i komfortowej jazdy, a amortyzatory są ich kluczowymi elementami. Oczekuje się, że globalny rynek amortyzatorów samochodowych będzie rósł ze względu na rosnący popyt niezależnie od rodzaju technologii napędowych samochodów. Producenci koncentrują się na innowacjach zarówno w projektowaniu amortyzatorów, jak i procesów produkcyjnych, dążąc do większej efektywności energetycznej i materiałowej. Analiza produktu, układ linii i kontrola jakości są niezbędnymi elementami procesu montażu i testowania amortyzatorów, zapewniając, że gotowe produkty mają wysoką jakość i spełniają wymagania rynku. Prawidłowy projekt linii montażowej amortyzatorów jest warunkiem wydajnej produkcji masowej, wymagającej skrupulatnego planowania produktów, procesów i układu linii. Metodologie, takie jak concurrent engineering, pomagają w efektywnym rozwiązywaniu problemów projektowych, wspierając innowacje i współpracę między projektantami, inżynierami i decydentami. Celem projektu opisanego w tym badaniu było opracowanie modułowej linii montażowej amortyzatorów integrującej innowacyjne funkcje w celu zwiększenia wydajności, w tym wysoką dokładność pomiaru w testach funkcjonalnych, automatyzację i skrócenie czasu cyklu, spełniającej zróżnicowane potrzeby producentów OEM i firm Tier1 na całym świecie. Projekt ten uzyskał dofinansowanie w ramach Programu Operacyjnego Inteligentny Rozwój 2014-2020 pod oznaczeniem POIR.01.01.01-00-1029/17-00. Linia została opracowana, przetestowana i wdrożona, a niniejsze opracowanie koncentruje się na opisie poszczególnych modułów linii.

Słowa kluczowe: amortyzatory samochodowe, linie montażu amortyzatorów, concurrent engineering, projektowanie linii montażowej

1. Introduction

Suspension systems play a key role in ensuring a safe, smooth and comfortable ride. Their essential components are damping elements, which are typically telescopic hydraulic dampers. The use of dampers in cars is crucial for active safety or collision prevention. They enable maintaining the appropriate tire-to-ground grip on various types of surfaces and stabilizing the vehicle during driving and braking (Gardulski, 2009). It is therefore not surprising that with the growing demand for passenger cars and light commercial vehicles in emerging economies and the growing trend of electric and hybrid vehicles, the global automotive damper market is expected to grow at a CAGR of 5.4% over the next ten years (2023-2033) (Persistence Market Research, 2023). Manufacturers at the OEM (car manufacturers) and Tier1 (component suppliers) level are therefore looking not only for innovations in the design of dampers themselves but also in the modernization of their production. This applies particularly to the optimization of energy and material consumption and quality testing with appropriate precision.

1.1. Dampers types

Modern car suspensions are complex mechanical systems with damping and elastic elements. Dampers found in vehicle suspensions can be divided into two groups with several varieties: mono-tube and twin-tube (Fig. 1). Main differences between those groups was collected in Table 1.

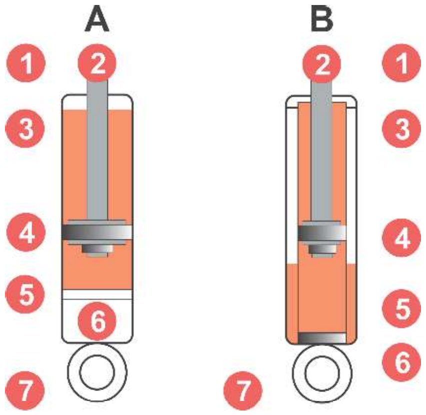

Fig. 1. Simplified drawing of the mono-tube (A) and twin-tube (B) variants. A(1) – external tube; A(2) – piston rod; A(3) – oil chamber; A(4) – piston valve; A(5) – floating piston; A(6) – gas chamber; A(7) – mounting element; B(1) – external tube; B(2) – piston rod; B(3) – pressure tube; B(4) – piston valve; B(5) – gas-oil chamber; B(6) – base valve; B(7) – mounting element

Twin-tube basic – consists of two cylinders placed one on top of the other: an internal pressure cylinder and an external reserve cylinder. There is a compression valve in the lower part.

Twin-tube gas – its general structure is very similar to the simple version. Nitrogen is introduced into the external cylinder at low pressure. This has resulted in a reduction of the foaming or aeration of the oil. The foaming phenomenon occurring when the temperature of the twin-tube system increases causes hydraulic fluid leakage. Dampers of this type predominate in modern vehicle suspensions.

PSD – position sensitive damper – another evolution of the twin-tube damper in the gas version. The pressure cylinder is additionally equipped with grooves here, improving the freedom of movement of the piston in the middle range of the stroke, in the so-called comfort zone. On the other hand, the piston moves with significantly less freedom when driving on very irregular surfaces, resulting in a “stiffening” of the suspension and greater control over the vehicle – the so-called control zone.

ASD – acceleration sensitive damper – change in the design of the compression valve enabling a faster response to individual unevenness.

Table 1. Mono-tube and twin-tube comparison

Mono-tube	Twin-tube
Main differences	
• The housing is also a cylinder with a piston rod guidance system, oil and gas placed inside • A floating piston separates the oil and gas chambers • High gas pressure	• Pressure pipe, cylinder is placed inside the outer pipe (housing). The piston rod moves inside the pressure pipe. • Oil and gas chambers are not separated • Low gas pressure
Pros	
• Stable damping force over time due to larger oil capacity and better heat dissipation • Larger piston valve allows for greater precision while generating low damping forces • No restrictions on the mounting angle • Easier heat dissipation • No oil aeration due to the separation of the chambers	• It is easier to ensure sufficient lift with a shorter structure length • The use of a base valve allows the use of low gas pressure – driving is more comfortable • Low gas pressure avoids seal stress and reduces friction • The damper remains functional with minor damage to the outer tube
Cons	
• Construction more susceptible to damage (single tube, which is also a housing) • Maintaining sufficient stroke is made more difficult by the serial arrangement of the chambers, the greater length of the damper for the same stroke • High gas pressure causes a "stiffer ride", greater seal stress and friction	• Lower oil capacity • Smaller piston rod • The design limits the possible mounting angles • The oil and gas chambers are not separated, which causes aeration and foaming as the temperature increases

Mono-tube – initially patented in the 1950s by Bilstein (Shelton, Chris, 2017). consists of a single pressure cylinder containing both gas and oil medium. It has two pistons: a working piston and a floating piston, which move inside the pressure tube. Both pistons completely separate the liquid and gas components of the damper. This type of damper has a longer design than the twin-tube, and has no directionality of assembly. The nitrogen pressure is 1,8÷2,5 MPa.

The output force of the damper is described by a complex function of the hydraulic valve characteristics, dimensions, oil properties, gas pressure and fluid phenomena, e.g. cavitation. Numerous works (Lang, 1977; Duym, Steins, Reybrouck, 1997; Farjoud, Ahmadian, Craft, Burke, 2012; Ferdek, Łuczko, 2012; Czop, Sawik, 2011) describe methods of modeling the output damping force and provide specific models, such as the dynamic model of the Lang twin-tube damper (Lang, 1977). These models are of key importance for the functional characteristic test stations of dampers (Sikora, 2017).

1.2. Assembly lines design process basics

Assembly lines (ALs) represent a fundamental method in mass production environments, facilitating efficient product assembly through the use of workers, dedicated machines, or robots. The design of assembly lines is crucial as it directly impacts the efficiency and productivity of manufacturing processes. The primary objective of assembly systems is to enhance line efficiency by maximizing the throughput-to-cost ratio, which is essential for maintaining competitiveness in today's demanding markets (Adham et al., 2013; Nourmohammadi, Eskandari, 2017).

Assembly line design (ALD) involves several critical components, including the development of products, processes, and plant layout, which must be meticulously planned before the actual construction of the assembly line. This planning phase is vital as it ensures that the assembly line operates smoothly and efficiently once implemented. The interaction of these components throughout various stages of the ALD process is crucial for achieving optimal performance (Bortolini et al., 2017; Triki et al., 2017). For instance, the assembly line balancing problem (ALBP) is a well-known challenge that arises during the design phase, where the goal is to allocate tasks among workstations in a manner that minimizes idle time and maximizes productivity (Nourmohammadi, Eskandari, 2017; Cohen, 2013).

Product analysis includes a review of the product design, adhering to standard 'design for assembly' (DFA) principles and task precedence constraints. The module focused on operating modes and techniques suggests suitable assembly methods, as well as possible modes for each task: manual, automated or robotic (Gao et al., 2019).

The line layout (LL) problem is divided into logical and physical layouts. Developing the logical layout involves distributing tasks among the stations along the assembly line, whereas the physical layout determines the placement of stations, resources, conveyors, buffers, and other equipment on the factory floor. The logical LL includes challenges such as assembly line balancing (ALB) and resource planning (RP). In manual assembly lines, balancing aims to equalize the workload across stations. For hybrid assembly lines (HALs), where operations can be performed manually or with robots and automated machinery, resource planning assigns resources to tasks and allocates tasks to stations (Yamada et al., 2022).

Companies implemented various practices and tools, collectively known as concurrent engineering (CE), to enhance their product development processes. CE is fundamentally characterized by the integration of diverse expertise to address design challenges effectively and efficiently. The essence of CE lies in assembling the right individuals at the right time to collaboratively identify and resolve design problems. This approach fosters a multidisciplinary environment where various stakeholders, including system engineers, designers, and decision-makers, can engage in real-time discussions and problem-solving activities. As noted by, the application of multidisciplinary design optimization methodologies enhances collaborative efficiency among these groups, allowing for a more cohesive approach to design challenges (Brevault et al., 2017).

The objective is to minimize the overall cost of the line by simultaneously addressing design considerations (e.g., station space, cost), operational factors (e.g., cycle time, precedence constraints, resource availability), and designer preferences (e.g., task complexity) (Nag, 2023). This leads to a definition of crucial conditions for a company to be competitive on the market: quality, reduced time and low costs for the development of new products (Rihar, Žužek, Kušar, 2020).

1.3. Car dampers production process

The first stage of damper production is forming tubes from a sheet of steel. The cut steel strips undergo a forming process using rotating rollers and are automatically welded after shaping.

The finished tubes are cut to the appropriate length depending on the type of damper. For further consideration, the definition of the damper type was adopted as a production reference, i.e. a set of parameters defining the purpose of the damper, its dimensions, functional parameters and appropriate settings of the production machines on the line. The length of the tube cutting is precisely defined in the damper design and varies depending on whether it is a pressure or external tube. The external tube usually goes through additional processes related to ensuring the appropriate interface between the damper and the car's steering knuckle, e.g. the compression process of one of the ends, welding the pin or the steering knuckle clamp.

In the production of twin-tube dampers, valves controlling the internal oil flow are installed in the pressure tube, as well as additional elements in the form of rings or springs, depending on the valve design.

The rolling machine crimps the valve end, closing the bottom of the pressure tube. The outer tube is closed with a cover with a welded mounting eye, which is the so-called basic system. The assembled subassembly can be loaded with the open part upwards onto the final assembly line, where the pressure tube subassembly with the piston rod is fitted and inserted. It is also filled with oil. Finally, the damper is closed by assembling a steel piston, pressure valve and piston rod guide with a seal. The gas component in the form of nitrogen is introduced before closing the piece. Finally, various types of connectors, sleeves or protective collars made of steel or rubber are assembled.

In the production of mono-tube dampers, the tube is manufactured in a similar way to the twin-tube outer tube. After closing on one side and welding, the tube ends are sent to a washer and then to the assembly line. There, the geometry is checked, oil is filled, the floating piston and piston rod unit are assembled, functional tests are performed, gas is filled and the other side of the cylinder is closed.

2. Damper assembly and testing line

2.1. Project main objective

The project aimed to develop and showcase a hybrid technological line for the assembly and testing of automotive dampers with various process improvements. Funding for R&D work was obtained. The project's outcomes were implemented within the operations of ELPLC S.A., under Priority Axis I of the Smart Growth Operational Program 2014-2020 – Support for R&D activities by enterprises. The initiation of this project was also driven by extensive experience in designing machines and production lines for automotive industry, using concurrent engineering practices and tools.

2.2. Target market

The implementation of the Project's results directly addresses the identified needs of the OEM and Tier 1 companies operating in the global market. These needs are primarily related to increasing the efficiency and flexibility of technological processes associated with the assembly and testing of the functionality and quality of car dampers. The target group highlighted the necessity of solutions that will allow them to increase production capacity, be cost-effective in terms of purchase and maintenance, and accelerate the fulfillment of orders. Moreover, the technological lines should offer various quality improvements, such as increased accuracy in measuring the damping force or gas filling process optimization, and enable the customization of functionalities to adapt to constantly evolving market trends.

2.3. Purpose of the line

The line presented in the study (Figures 2, 3, 4) assembles a ready-made twin-tube cylinder with a piston rod subassembly and a floating piston. The input components are: a mono pipe closed on one side with a welded tip, a ready-made piston rod assembly, a cap, oil, nitrogen, and labels. At the output of the line, the assembled damper is expected, ready for final assembly. Modularity was assumed in order to flexibly adjust the pallet flow and exchange stations, as well as easy conversion to various references.

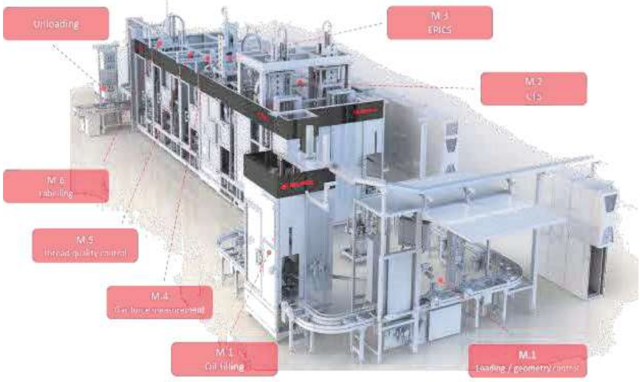

Fig. 2. 3D model with marked modules

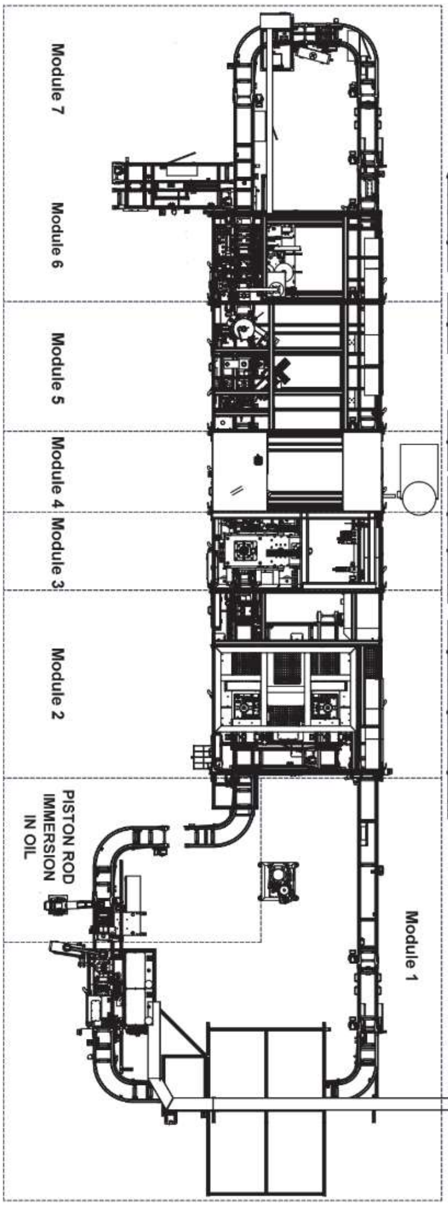

Fig. 3. Assembly line layout

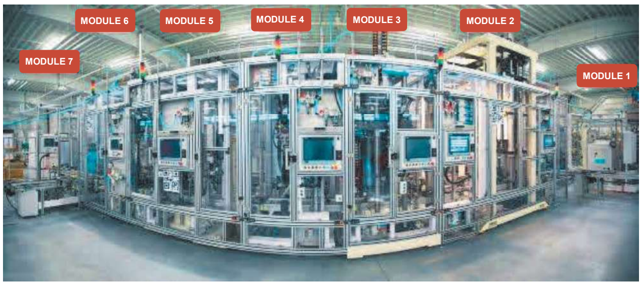

Fig. 4. Assembly line panoramic photo

2.4. Main parameters for manufactured dampers

During development work, the widest possible range of line availability for typical product dimensions was taken into account (Table 2). At the same time, efforts were made to maintain the ease of retooling.

Table 2. Main parameters ranges

Parameter	Value, range
Tube diameter range	30 ÷ 60 mm
Tube height range	120 ÷ 600 mm
Product height range	120 ÷ 1000 mm
Maximum product weight	8 kg
Oil dosing volume	60 ÷ 600 ml
CTS[1] – test force	-6500 ÷ 6500 N
CTS – stroke range	0 ÷ 400 mm
CTS – test speed	0,5 ÷ 1000 mm/s
CTS – maximum acceleration	10 g
CTS – acceleration curves	sin, triangle, trapezoid
CTS – test frequency	16 Hz
Damper Closing Force (EPICS)	45 ÷ 150 kN
Gas pressure (EPICS)	2,5 MPa max.
Gas force control	20 ÷ 500 N
Cap diameter	40 ÷ 80 mm
Spring bed ring – diameter	30 ÷ 300 mm
Spring bed ring – position	25 ÷ 100 mm
Transport pallet size	320 x 320 mm

[1] CTS – functional characteristics tester.

2.5. Line modules

2.5.1. Module 1 – loading, geometry inspection, oil filling and assembly of the piston rod unit

The operator loads the finished pipe onto the transport pallet and confirms the loading. The pallet moves to a measuring gate that checks the pipe diameter and height, so that unsuitable or defective pipes can be eliminated at an early stage.

The inspection is carried out using a vision system with a fixed focal length lens. The system is mounted on an electric linear module with a maximum range of 600 mm (Fig. 5).

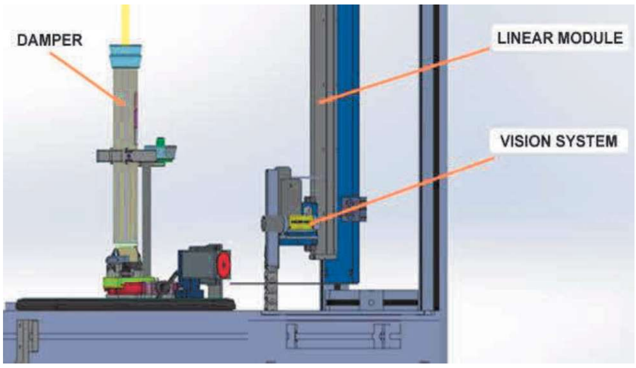

Fig. 5. Geometry control gate schematic

After positive geometry verification, the pallet moves automatically to the oil filling station. Oil is dosed into the damper chambers using a precise servomotor control algorithm and pneumatic solenoid valves. The maximum capacity of the filling cylinder is 780 ml. This allows dosing in the designed range of

60÷600 ml and avoiding operation over the full range of the actuator movement.

The piston rod insertion station in this module is prepared to be operated by a 6-axis universal robot that performs this monotonous and tedious operation.

2.5.2. Module 2 – functional characteristic tester

The actual measurement of the damping force is controlled using a force transducer with an appropriately increased range. The test force of 6.5 kN is confirmed by simulation with an additional margin. The force measurement is performed in a specific working position in range 0 to 400 mm.

Linear motors are characterized by maximum operating dynamics, allowing them to achieve high speeds quickly. The movement per unit of time is monitored using an external measurement system controlled by real-time systems.

The dynamics of the system related to its mechanical structure (Fig. 6), the path measurement resolution and the stability of readings allow for a wide range of speeds from 0.5 mm/s to 1500 mm/s. This range is also sufficient to perform functional tests of most dampers manufactured on the market.

Fig. 6. CTS testing tooling

2.5.3. Module 3 – closing and gas filling (EPICS)

Closing the damper consists in rounding the upper part of the tube while simultaneously gassing and maintaining the appropriate gas pressure in the damper.

The closing system is driven by a servo drive (Fig. 7). Then, a planetary screw coupled to the gas-rolling head is driven by a gear (Fig. 7). The system reaches the point where a specific force value occurs. The path is therefore dependent on the point where the set force occurs, and this depends on the type (production reference) of the damper and its dimensions, and is therefore insensitive to the tolerance of the length of the tubes.

The aim of developing the station was to reduce cycle time, which was achieved by integrating two operations in one machine. In classic solutions, the gas filling with initial closing and final closing stations are separated. The result of the development of EPICS is over 50% shorter cycle time. Use of real-time system and single cycle chart makes data analysis simpler.

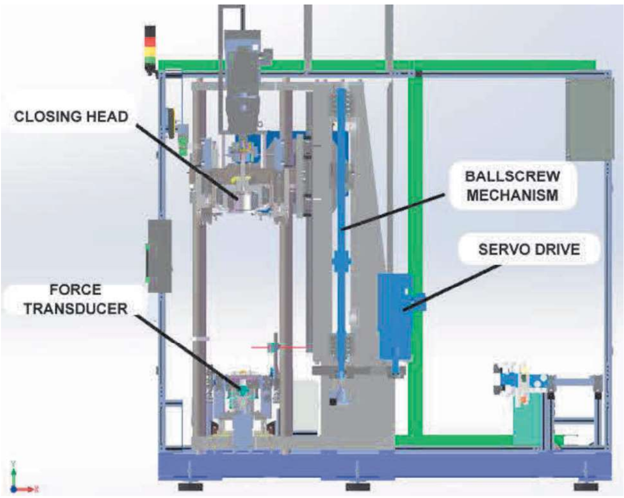

Fig. 7. EPICS station main elements

The force measurement is performed using a resistance strain gauge with a range of 250 kN. It allows for the measurement of forces in the assumed range from 45 kN to 150 kN. Oversizing the transducer allows for increasing the durability of the system thanks to a significant range reserve and resistance to significant exceedances of the assumed range.

At the EPICS station, nitrogen pressure in the damper is achieved up to 2,5 MPa. A dedicated pneumatic system and a head and cylinder sealing assembly have been designed for this purpose (Fig. 7). Nitrogen under pressure is supplied to the damper in the closing head.

2.5.4. Module 4 – gas force measurement

Gas force control in the typical range of 20-500N is a way to assess the correctness of the Module 3 (EPICS) operations. The measurement is carried out using a resistance strain gauge with a range of 1.25 kN and a dedicated rotation system (Fig. 8). The adopted range of force values is typical for the vast majority of dampers manufactured. Module 4 also includes a piston rod thread blow-out system. Contaminants on the thread could falsify the result of the visual thread inspection on the next module.

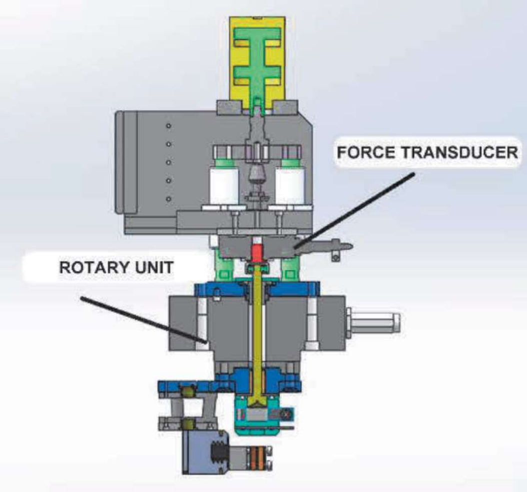

Fig. 8. Gas force test unit

2.5.5. Module 5 – Thread quality control and cap assembly

The cap diameter taken from the transport pallet depends on the shape and dimensions of the gripper jaws (Fig. 9; Fig 10). Thanks to the retoolable jaws (yellow elements on Fig. 9 and Fig. 10), it is possible to ensure clamping of the overlay with a diameter in the range of 40-80 mm. For typical products on the line, a gripper with a stroke of 30 mm per jaw, a closing force of 260 N and an opening force of 300 N was selected. The gripping system was equipped with a special system for quick jaw retooling with positioning. Below is a simulation of the clamping possibilities of jaws designed for diameters of 60 mm (Fig. 9). Additionally, the station has thread quality control performed by an original vision system with hi-res cameras.

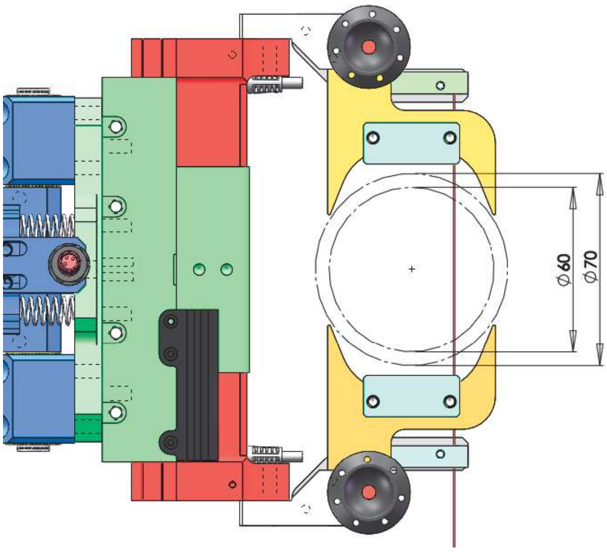

Fig. 9. Cap gripper jaws – open position

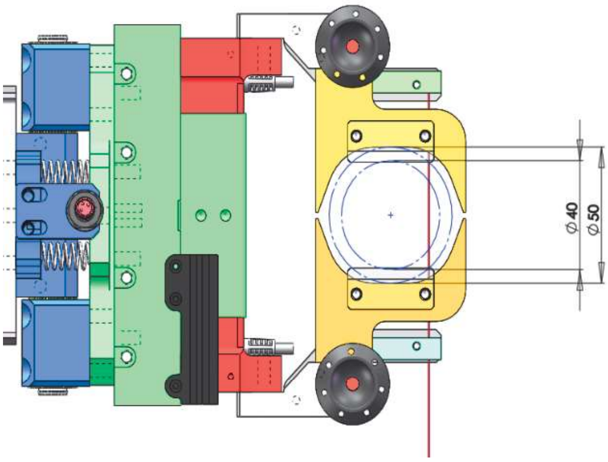

Fig. 10. Cap gripper jaws – open position

It is important to consider the clearance needed when the jaws approach the cap and the proper adhesion and holding of the cap after crimping. Another limitation is the distance between the cap collection point and its mounting point on the damper. In our case, it is 90 mm x 90 mm. This is a range optimally selected for the typical cap diameters.

2.5.6. Modules 6 and 7 – labelling, final control and unloading

The final stage of the production flow is labeling the damper, final inspection and unloading for further assembly. The presented line was based on a Bosch Rexroth BS 2/R series transport system with a metal accumulation chain. The load capacity of the transport drive is 1.5 kg/cm, which means that the weight of the 320x320 mm pallet with the component cannot exceed 48 kg. The recommended optimal range for this transport system is 20-25 kg, the project assumed 23 kg. The pallet itself with the socket and RFID carrier weighs approx. 15 kg, which gives us a possible maximum component weight up to 8 kg. This is supported by ergonomic considerations and typical values for manufactured dampers. Before unloading, the damper passes through the final inspection station. The following product parameters are checked using a vision system:

- Tube diameter: 30÷60 mm,
- Tube height: 120÷600 mm,
- Spring bed ring position: 25÷100 mm,
- Product height: 300÷1000 mm.

3. Summary

The planned milestones in the form of individual modules and the following innovative features of the line were achieved:

a) modularity of the installation,

b) high accuracy of measurement on testing stations,
c) high automation of the technological line, robotization of piston rod immersion,
d) cycle time reduction (gas filling and closing module),
e) increased service life of modules / technological line.

The designed and built technological line meets required parameters covering a wide group of typical dampers manufactured in the world (see Table 2). After completing the design, assembly and programming work, the line was launched. A test run of components was carried out on each of the modules and their verification after the process and reference values were set. All modules have been validated in test production using real components. Finally only 2 operators are required for full service of the line – at the loading station (module 1) and unloading (module 7).

Acknowledgments

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All work was supervised by a team led Robert Tomasiewicz. The research team carried out conceptual work under the leadership of Piotr Brzyszcz, with the support of Grzegorz Domagała. The team of programmers carried out work under the leadership of Sławomir Gleisner. Technologists – Anna Bąk and Wojciech Noga were responsible for preparing the documentation for production. The automation team carried out the work under the management of Tomasz Soboń. The mechatronics team carried out the work under the management of Paweł Tryba. As a result of the work of the R&D staff, full 2D and 3D documentation was prepared for future use.

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