27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-2236
INTEGRATED PRODUCT DEVELOPMENT METHODOLOGY APPLIED TO A RESONANT FATIGUE TESTING BENCH FOR SHAFTS AND CRANKSHAFTS

Artur Cantisano
arturc@ita.br
Luiz Aun Fonseca
luizaun22@gmail.com
Jefferson de Oliveira Gomes
gomes@ita.br
Ronnie Rego
ronnie@ita.br
Eduardo Garcia Muño
munoz@ita.br
Instituto Tecnológico de Aeronáutica. Department of Aeronautical and Mechanical Engineering. Praça Marechal do Ar Eduardo Gomes, 50, São José dos Campos – SP, Brazil.

Tiago Cristofer Aguzzoli Colombo
tiago.colombo@fatec.sp.gov.br
Faculdade de Tecnologia de São José dos Campos – Fatec Prof. Jessen Vidal. Avenida Cesare Monsueto Giulio Lattes, 1350, São José dos Campos – SP, Brazil

Abstract. *Modern mobility has brought challenges to the automotive sector, as the requirements for increasing energy efficiency and reducing weight and CO2 emissions are becoming increasingly severe in all world markets. Of the existing technical strategies to achieve these goals, engine downsizing is currently one of the most applied methods. Engine downsizing is based on smaller and more fuel-efficient engines, without impairing their efficiency. Nonetheless, such downsizing approach has a direct impact on critical engine components, such as shafts and crankshafts. When downsized, these components are prone to higher requirements related to mechanical strength and performance. Due to the predominance of cyclic mechanical loads in the engine, shafts and crankshafts are especially prone to fatigue failure. Considering that the manufacturing chain of such components involves numerous sources of residual stresses, it is thus mandatory to carry out durability tests on these components, especially considering the trend of engine downsizing. Thus, the objective of this study is to present an IPD - Integrated Product Development Methodology to the development of a fatigue testing bench for shafts and crankshafts. The applied methodology followed steps of informational, conceptual, and detailed design, gathering industry requirements related to modern automotive engines. The testing bench was developed allowing tests of torsion and bending, which are the predominant efforts in these components, with the differential of allowing tests on both shafts and crankshafts of different geometries and sizes. The IPD methodology employed considered the need of a fast specimen exchange, with a control system that adjusts bending and torsional moments applied to the specimen automatically, a monitoring system against force peaks and automatic shutdown at the end of the test. In total, more than 100 bending fatigue tests were carried out in the developed testing bench, totaling 733 million cycles, with an average of 550 N.m of bending moment. In torsion, 13 tests were performed, with 150 N.m of torque, totaling 1.57 million cycles. The development of the testing bench using the IPD methodology also allows an expansion of the investigations carried out with an increased robustness and reliability combined with a reduction of testing costs.*

Keywords: *Integrated Product Development, Resonance, Fatigue, Shafts, Crankshafts.*

1. INTRODUCTION

Since the agreement to reduce CO_2 emissions to 140 g.km^{-1} in 2008, the reduction of fuel consumption has been a major requirement regarding the development of new internal combustion engines (ICEs) in the automotive industry. According to Stephenson (2009), the key technologies applied to improve engine operating efficiency currently are: direct injection, variable valve timing, self-detonation control and engine downsizing. Of all these possibilities, engine downsizing is one of the most efficient and with fast implementations in the current market (ATKINS; KOCH, 2003). This is done by shifting the operating point to a region of higher power efficiency consumption, while the use of turbo compressors raises the average pressure of the pistons, enabling a better relationship between power density and fuel consumption (BAE; BAE, 2005; STEPHENSON, 2009). This technological trend has an impact on requirements that require overcoming the current components in mechanical strength, mass reduction and energy efficiency. Therefore, the crankshafts play an essential role during the development of new ICEs, as it is responsible for transferring all the power produced by the engine, as its main function is to convert the linear movement of the pistons into rotary (VILLALVA; JUNIOR, 2010; WILLIAMS; FATEMI, 2007). As a main component in ICEs, the crankshaft directly influences noise and vibration, mechanical efficiency, production cost and the durability of the engine (CEVIK et al, 2012).

Mechanical components such as the crankshaft have the fatigue endurance limit as one of the most important and critical factors considered in their dimensioning and manufacturing. In-depth knowledge of the fatigue durability of such components is mandatory, and it can be influenced by many different aspects. In addition to geometric and raw material factors, the manufacturing chain involved in the production of machine elements for ICEs may have a direct influence on the durability of the final component. Considering crankshafts, the manufacturing chain basically begins with the forging or casting of a component with a geometric shape close to that of the final crankshaft. Subsequently, it is subjected to roughing by milling, deep rolling or induction hardening and finishing by grinding. The deep rolling and induction hardening manufacturing stages have the objective of strengthening the material, thus increasing the fatigue strength of the final component (LOVE; WAISTALL, 1954). The increase in fatigue strength occurs by introducing compressive residual stresses to the surface and by the improvement of the material mechanical strength due to hardening or alteration of the microstructure of the material (CASARIN, 2007; KO et al, 2005). Nonetheless, due to uncertainties arising from fluctuations during the manufacturing process, crankshaft design becomes complex and empirical in nature.

Considering the above, experimental fatigue life tests are necessary for an accurate prediction of the durability of these components. Traditionally, the fatigue endurance limit is experimentally obtained by expensive, time consuming mechanical tests, as it commonly requires complex testing infrastructure and specialized labor. This is due to the fact that the conventional tests for fatigue investigations such as rotational bending or tensile-compression that are performed with standardized smooth specimen do not reproduce the operating efforts and manufacturing influences on the properties of automotive crankshafts. Therefore, engine developers need more representative tests to verify the durability of engine components. One of the options is the engine bench test, which is generally applied to the final stages of new product development, as it provides results for evaluating the system rather than a component. The difference in this test is the loading and environmental conditions of operation, which are closer to the real component operating conditions. This test has limitations regarding the influences of other components, along with its high cost and the fact that the test is performed with operating efforts, that is, values below the limits defined by design. The third option consists of testing the component in a fatigue rig test developed for testing crankshafts specifically, with the aim to converge in a same testing structure the reproduction of the operation mechanical loads during the operation, the mechanical properties of the manufacturing material and the influence of the manufacturing chain on it.

The requirements severity increase in terms of crankshaft durability brought by engine downsizing require new testing benches that allow further component optimizations, demanding changes to the currently used testing methods, to reduce the required testing time, enable the possibility of applying combined and increased loads, use of more complex crankshaft geometries in order to reduce the test´s cost and duration. The aim of this paper is to present a method based on Integrated Product Development – IPD for the development, manufacturing and validation of a crankshaft fatigue test bench, taking into consideration its advantages, limitations and the possibility to evaluate the functional performance of new crankshaft designs.

2. MATERIALS AND METHODS

The Integrated Product Development process is carried out in phases by a multidisciplinary team, where each phase provides inputs that substantiate the following development stages, increasing the understanding of the product outputs face to the proposed requirements. The process can be described in three major phases: Informational Project, Conceptual Project and Detailed Project.

The Informational Project phase consists in gathering analyzing data about the project demands, including the entire product´s lifecycle, in order to define a solid and coherent product scope and the requirements that shall be met. To do that, the customer and major stakeholder´s requirements, needs and expectations are to be identified. This shall be done through meetings and interviews with the customer participation (ROZENFELD et al., 2006).

The House of Quality, the first QFD (Quality Function Deployment) matrix, is employed to translate the customer requirements into product requirements, considering their importance according to the customer´s point-of-view, by relative weighted attributes. A proper statement shall be written for each requirement, so that its completeness and correct interpretation is ensured. The completed Informational phase outputs enable initiating the Conceptual phase (ROZENFELD et al., 2006).

The Conceptual Project phase aims finding viable solutions by means of searching and arranging potential alternatives for each of the functionalities necessary to meet the defined requirements (ROZENFELD et al., 2006). The development of alternatives is a free creation process, driven by the product and project requirements. Firstly, the product is modelled by means of a Functional Analysis, identifying major functions and deploying sub-functions. The importance of the requirements is cascaded down to the sub-functions by weighing their relative importance.

The sub-functions drive the Morphological chart elaboration, carried out by means of multidisciplinary working sessions with the project team, using brainstorming and other tools to identify and generate several possible alternatives for each of the product´s required sub-functions. Then different sets of these sub-functional solutions are combined to pile up concurrent physical architecture alternatives for the product, As can be seen in Figure 1. The combinations are evaluated regarding their ability to deliver the sub-functions upstream to the major functions that collectively represent the product. The best ranked alternative among those concurrent solutions is the one which better meets the product´s expected performance, according to the stakeholder´s point of view. The winning alternative shall be taken to the next step. Other potential alternatives may also follow to the Detailed Project Stage, as Concurrent Engineering alternatives.

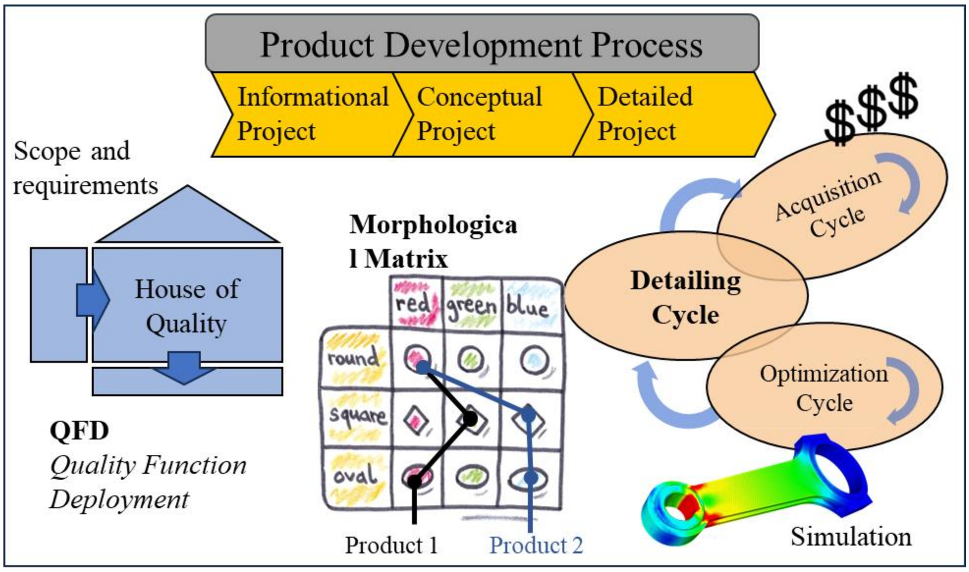


Figure 1 - Integrated Product Development Cycle and typically used tools.

The Detailed Project Stage is a crucial step of the IPD process, where the product concept is evolved to a detailed design, enabling it to be fully described from an engineering perspective, enabling the purchasing of materials, components and sub-systems and its manufacturing and overall assembly. The technical requirements are the boundary conditions that drive the dimensioning and selection of materials and components. As Figure 1 shows, the Detailed Design Stage has three cycles that retrofeed themselves, as components and sub-systems are designed, selected and optimized. This demands a high level of integration of the cycles, of the teams and engineering processes within the Project Team organization.

3. RESULTS

Considering the numerous intermediate steps involved in decision making throughout the Product Development Process, this study will present significant outputs from the three IPD process phases. During the Informational phase, the House of Quality will be showcased, providing a detailed description of key requirements. Moving on to the Conceptual Project phase, the Morphological Chart will be presented, illustrating various proposed alternatives for the product's main functions. Additionally, will be provided a description of the selected solution to be implemented. In the Detailed Project phase, a thorough presentation will be made regarding the dimensioning and selection process employed for the main components. This comprehensive overview aims to provide insight into the meticulous steps taken to guarantee optimal performance and functionality.

3.1 Informational Project

Preliminary meetings were carried out to identify major characteristics and functions that the equipment should provide, per customer perspective. Initially, the characteristics converged to robustness of high and low cycle fatigue tests; safe operation; low energy consumption; reproducibility, precision, ease of operation; continuous operation; low test duration; automatic control of test stresses; real-time data acquisition. Based on the scope, a set of requirements was prepared to satisfy those characteristics, which was then assessed by the customers in terms of relative importance for the product. After a sequence of discussions and reformulations of the requirements and relative weights, a consolidated Customer Requirement document was published (Table 1).

The load simulation receives the highest score, highlighting the rigorous attention given to carrying out tests that faithfully reproduce the component's operating conditions. Following closely with a rating of 4 are several critical factors: test duration, result reproducibility, low test malfunction rates, and low operating costs. The interrelationship between these four ranking requirements underscores the dedicated search for a product that combines cost-effectiveness with immediate results. The high rate of test malfunctions and lower reproducibility of results, indicated by a narrower standard deviation, require a larger sample of tests to achieve the desired level of accuracy. Thus, it is evident that optimization efforts focus both on operational cost and time to obtain results.

The objective of Product Requirements is to fulfill the Customer Requirements, establishing a crucial link between the two. This connection is assessed through a relationship intensity attribute, which is rated on a scale from 0 to 10. For instance, load simulation (customer requirement) exhibits a strong relationship grade of 10 with the Torsion and Bending test (product requirement), as well as a grade of 8 with both the test specimen fixature and the actuator power (product requirements). A higher grade indicates a more significant relationship. By evaluating all these relationships, the importance of each product requirement can be determined by calculating the weighted sum of the relevance assigned to the Customer Requirements and the relationship grade associated with each specific product requirement.

Table 1 - House of Quality

Product requirements / Customer requirements	**Importance (1 to 5)**	**Relative Importance (%)**	Torsion and bending test	Test loading	Operating frequency	Uninterrupted test	Number of specimens	Test load accuracy	Measurement accuracy	Intuitive software	Specimen fixture	Simplified preparation	Non-destructive crack testing	Test room heat generation	Standard components	Stability to external interferences	Actuator power	Control system
Load simulation	5	13%	10		7			2	3		8						8	
Low test time	4	11%			10	9	8	4	5	2		2	4		4	3		10
Results reproducibility	4	11%			2	10	7	10	10		9	2				7		6
Easy to change parameters	2	5%	2	10						7								8
User-friendly interface	2	5%	2							10								
Simple mounting	1	3%	7	8							10	8			4			
Visual inspection of cracks	3	8%	1			8												
Do not heat up the test room	2	5%		2										8			6	
Easy to replace parts	1	3%	6		4						8				10			
Low test malfunction rates	4	11%	2	5												5		
Low operating costs	4	11%		10	3					4		4	3			2	8	5
Low maintenance costs	2	5%	8	4							6				8		4	
Operator safety	4	11%	3	8	6		7		6	3				6				3
Absolute Importance (0 to 10)			2,89	3,47	3,24	2,63	2,32	1,74	2,61	1,84	2,79	1,05	0,74	1,05	1,21	1,79	2,42	2,95
Relative Importance (%)			8,3	10,0	9,3	7,6	6,7	5,0	7,5	5,3	8,0	3,0	2,1	3,0	3,5	5,2	7,0	8,5

Each of the product requirements are described and discussed below, in a priority order:

Requirement of test loading: Consists in the equipment´s capacity to apply the necessary loads to submit the test specimen to the fatigue test resistance stress load. This is an essential project requirement, as it is associated to the product´s main function.

Requirement for operating frequency: The fatigue occurs with the application of a dynamic force and the failure is proportional to the number of cycles and the applied stress. Increasing the operation frequency reduces the test time. On the other hand, the increase of the frequency for a given load, increases the speed of moving components, increasing the risks of accidents. From an energy point of view, an increase in energy consumption is expected due to increased accelerations.

Control system requirement: Fatigue tests commonly take a long time to give results. Having an operator-independent test control system enables intermittent testing. This reduces operating costs and increases operator safety. The reproducibility of results should have a positive impact, as a stable control system can ensure small corrections in the system's operation.

Torsion and bending test requirement: The test bench must have the capability to simulate the operational stresses on the component. This can be characterized by two main types of loading: torsion and bending. Therefore, the ability to perform torsion and flexion tests is essential.

Specimen fixature requirement: The test specimen fixation device is responsible for ensuring the transmission of test load to the test specimen with repeatability, meaning it allows for consistent fixation in different setups. Due to the high level of commitment and the challenge of transmitting large forces, the use of commercial components becomes more difficult, while simplicity in test specimen assembly is desired. As a consequence, there is a negative impact on maintenance costs.

Uninterrupted test requirement: This requirement has a direct relationship with the test time, necessitating the design of systems that do not require adjustments during the testing period. Interruptions can alter test reproducibility and increase result deviations. However, for visual inspection of cracks during the test, it may be necessary to stop the test.

Measurement accuracy requirement: Measurement accuracy impacts the simulation of forces, overall test time, and reproducibility of results. Additionally, measurement is important for general safety, including equipment, operator, and test data safety. The measurement should be capable of fast and accurate measurements, enabling an immediate response to the activation or deactivation of safety mechanical brakes, for example.

Actuator power requirement: The actuator power requirement has an impact on force simulation requirements and low operating costs. As the actuator power increases, so does the dissipated energy and consequently the temperature in the vicinity.

Number of specimens requirement: The more test specimens tested simultaneously, the shorter the average test time per specimen, resulting in faster results. This may have an impact on energy consumption, as the equipment will generate more force over time. It should not impact the deviation of results, but it may make the control system more complex to ensure equal loading on the test specimens accurately.

Intuitive software requirement: Through an intuitive interface for operator communication, human error can be reduced, operator training time can be minimized, and specialized operator training may not be required.

Stability to external interferences requirement: External factors' interference can influence test repeatability, measurement precision, and consequently increase result deviations. This will require a larger number of tests to achieve the same reliability, increasing operating costs and failure rates.

Test load accuracy requirement: The test force is the input of the system. Variation in the input force will directly reflect in result deviations at the end of the test. Therefore, to obtain statistically reliable results, the precision of the test force is crucial. At the same time, an increase in the standard deviation of results impacts the need for a larger number of tests for the same reliability and increases the total test time.

Standard components requirement: The use of easily available commercial components impacts maintenance costs and ease of component replacement. Although component failure is not expected, the total test time can be reduced, facilitating component replacement.

Simplified preparation requirement: Preparation is an important step in testing due to the responsibilities of proper test specimen fixation and configuration of test parameters. Thus, it impacts test time, result reproducibility, increased test failure rate, and consequently reduces operating costs.

Test room heat generation requirement: Although the method of operation is not defined, heat is generated by all actuation systems presented in the literature. The electric motor of rotating mass systems, the electrodynamic shaker, the electric motor, and the hydraulic pump of the hydraulic system will generate heat. Therefore, a ventilation system should be provided to maintain a pleasant work environment for the operator.

Non-destructive crack testing requirement: Non-destructive crack testing corresponds to methods such as liquid penetrant testing. To perform crack verification during testing, it is necessary to stop the test, which impacts test time and maintenance costs.

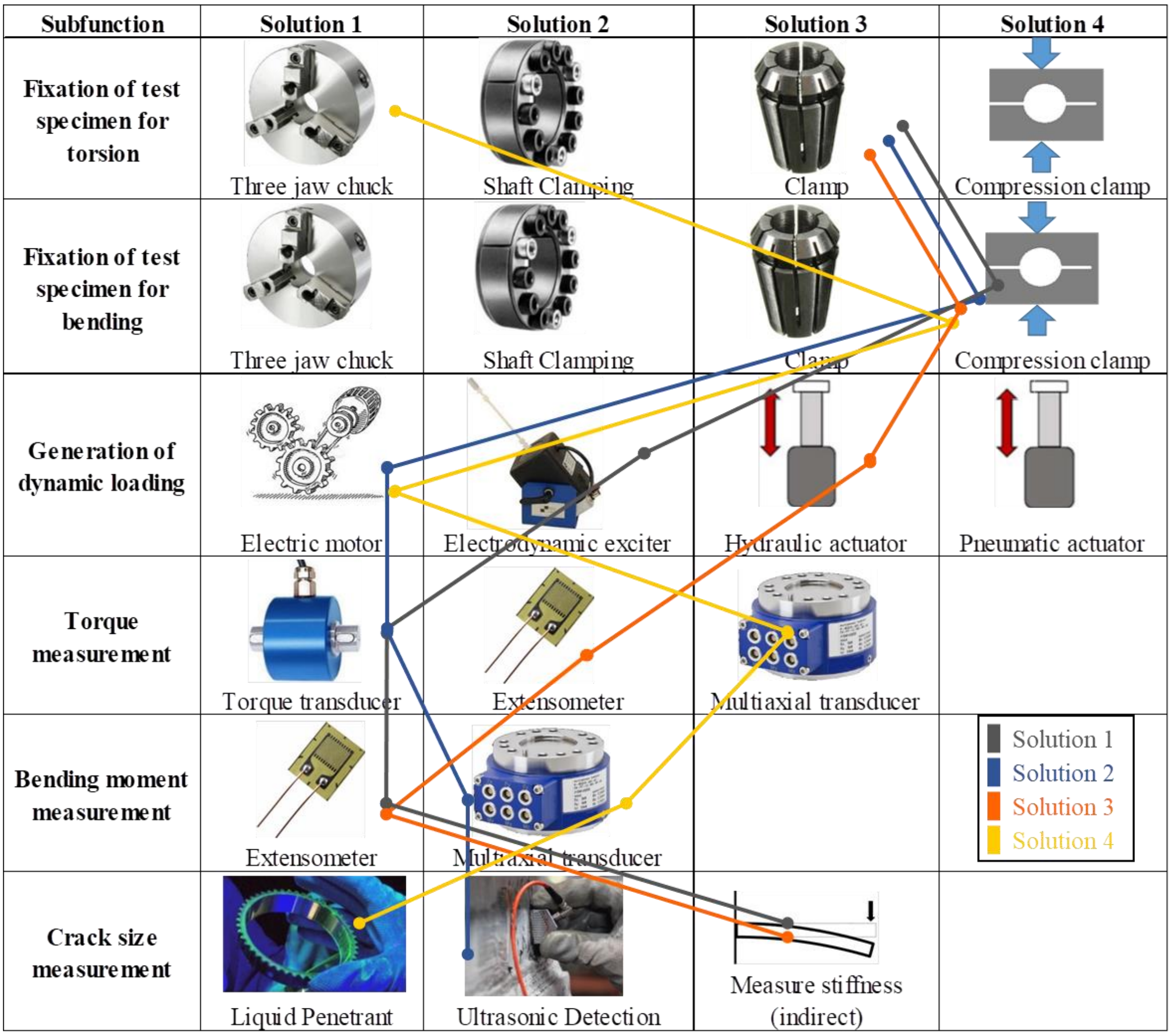
3.2 Conceptual Project

Based on the requirements defined in the information design stage, it was possible to proceed to the conceptual project to achieve the definition of the concept and necessary functions. Functions that satisfied the requirements and technical specifications were defined through functional analysis. The functions were correlated with the product requirements, and their weights were transferred. Thus, the importance of each function remains linked to its ability to satisfy the customer's requirements.

The most important subfunctions in the development of the product's conceptual design were selected, namely: test specimen fixation in torsion, test specimen fixation in bending, generation of dynamic loading, torsion measurement, bending moment measurement, and crack size measurement. Table 2 presents the possible solutions found for each subfunction, as well as the selected solution groupings for evaluation.

Fixation of test specimen for torsion: The function of fixing the test specimen for torsion is responsible for transferring the applied torque to the test specimen. The solution must be capable of withstanding the test forces, not introducing any influence on the applied stress, and allowing easy assembly. In the literature, torque values around 5000 N.m are found for determining the fatigue resistance of crankshafts. Although the three-jaw chuck allows for easy assembly and disassembly of the test specimen, this solution is limited to torques between 200 and 300 N.m. An alternative was considered with the three-jaw chuck aiming for a lower torque range, with the possibility of using customized jaws to increase the transmitted torque. The use of commercial clamping rings was found to be impossible due to the lack of rings in the required diameter and torque capacity. The compression collet is commonly found in crankshaft fatigue test benches for flexion tests, but the torque limitation also prevents its use for torsion. The proposed collet in Solution 3 was derived from tool holding collets used in machining centers. It is believed to be a viable solution due to its simplicity, possibility of multiple teeth, high torsional rigidity, and the use of a wedge mechanism to amplify the compressive force on the teeth.

Table 2 – Morphological matrix with the selected alternatives



Subfunction	Solution 1	Solution 2	Solution 3	Solution 4
Fixation of test specimen for torsion	Three jaw chuck	Shaft Clamping	Clamp	Compression clamp
Fixation of test specimen for bending	Three jaw chuck	Shaft Clamping	Clamp	Compression clamp
Generation of dynamic loading	Electric motor	Electrodynamic exciter	Hydraulic actuator	Pneumatic actuator
Torque measurement	Torque transducer	Extensometer	Multiaxial transducer	
Bending moment measurement	Extensometer	Multiaxial transducer		Solution 1 Solution 2 Solution 3 Solution 4
Crack size measurement	Liquid Penetrant	Ultrasonic Detection	Measure stiffness (indirect)	

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Fixation of test specimen for bending: The function of fixing the test specimen for bending is responsible for transmitting the applied bending moment to the test specimen. The compression collet solution is widely used in similar equipment found in the literature, indicating its capability to withstand the test forces (CHIEN et al., 2005; SPITERI; HO; LEE, 2007). Due to the lower order of magnitude of the bending moment compared to torsion, the ability to withstand flexion test forces is a requirement of lesser criticality compared to torsion fixation.

Generation of dynamic loading: The function of generating dynamic loading is responsible for applying the test forces in both flexion and torsion tests. The electrodynamic shaker was the highest-rated solution due to its ability to achieve high test frequencies and easy alteration and control of applied loads. The electric motor poses greater difficulty in altering parameters and controlling the load, as the loading comes from an eccentric mass, making the rotation frequency dependent on the generated load. The hydraulic actuator solution received the lowest rating due to its low test frequency.

Torque measurement: The measurement of test torque impacts the precision of measurements and, consequently, the precision of the applied test load due to the feedback control system. The strain gauge solution received the lowest rating due to interferences, noise, and instrumentation inaccuracies. The multiaxial transducer solution received an intermediate rating due to the high cost of the equipment. The torque transducer solution was the highest-rated solution due to its cost-effectiveness considering the achieved precision.

Bending moment measurement: The measurement of the bending moment impacts the precision of measurements and, consequently, the precision of the applied test load due to the control system. Both the multiaxial transducer and the use of strain gauges received low ratings, with the multiaxial transducer due to the high cost and strain gauges due to signal noise and low precision.

Crack size measurement: The function of measuring crack size impacts the identification of test completion, safety shutdown, and intermittent testing. The use of liquid penetrant resulted in a low rating due to the need for test interruption for measurement. The use of ultrasonic testing received a medium rating as it also requires test interruption but provides faster measurements. On the other hand, the indirect measurement solution using stiffness received the highest rating due to not requiring test interruption. This method involves monitoring the displacement amplitude of the test specimen since as the crack grows, the stiffness is reduced, resulting in increased amplitude of movement.

By grouping all the winning solutions, a pre-project can be prepared in order to make the projected visual proposal, as shown in Figure 2.

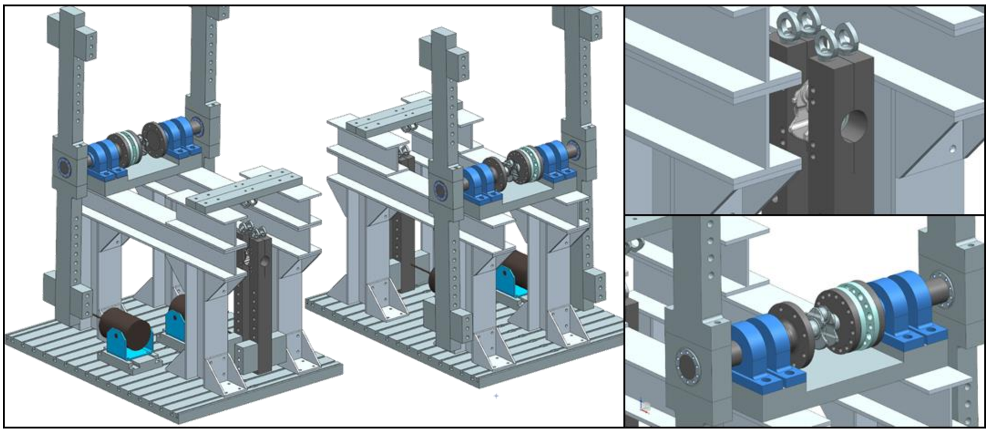

Figure 2 – Conceptual Project.

Therefore, it consists of equipment capable of independently conducting torsion and flexion tests, utilizing the resonance phenomenon, and actuated by an electrodynamic shaker. The bending test core is defined to be suspended by ropes, while the torsion test core is defined to be fixed with bearing supports. A T-slot table is chosen to enable positioning between the devices.

3.3 Detailed Project

The detailed project was developed according to an analysis of dependency between activities. This was a cyclical process. Initially, the focus was on determining the test load required by the test specimen since it is essential to achieve the required loads for the fatigue test. With the loads defined, it is possible to design the torsion and bending test cores, which include the fixtures of the test specimen and the support for test cores. The selection and sizing of the actuation system are enabled, and consequently, the design of the structure, sensor selection, and finally the control system, as shown in Figure 3.

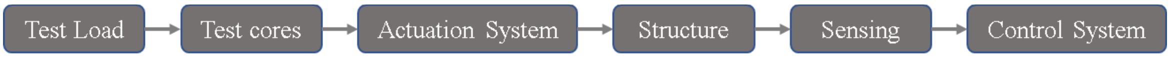

Figure 3 - Dependency structure between the different steps along the Detailed Project stage.

The test loading range was determined through finite element simulation of the test specimen, estimation of the fatigue strength of the test specimen material, and recommendations found in the literature. In order to allow the equipment to test different test specimens, the highest value from the references was adopted, consisting of a 1600 N.m capacity for bending moment and 5000 N.m for torque capacity. Therefore, the equipment is able to test different sets, from small components to Diesel engine crankshafts.

The sizing of the test cores was carried out considering the previously defined loads. Each component was designed, simulated using finite element analysis, the material was selected, and the manufacturing processes were determined. For the sizing and selection of the actuation system, the equation developed by Feng and Li (2003) was used. The authors developed the mathematical equation for the vibratory system in order to determine the deformation and moment in response to an excitation force at a certain frequency. This allowed for the selection of an electrodynamic shaker capable of generating the required forces. The chosen model was the 2110E from The Modal Shop, which has a maximum force of 489 N, a frequency range of up to 6500 Hz, and an amplitude of 25.4 mm (1 inch).

The equipment structure was designed to have easy height adjustment and positioning in relation to the table. The test cores are independent, except for the electrodynamic shaker, which needs to be repositioned to operate in each of the cores. The bending core is suspended by ropes and is located below the torsion core. Figure 4 shows a top view of the torsion core and a side view of the bending core.

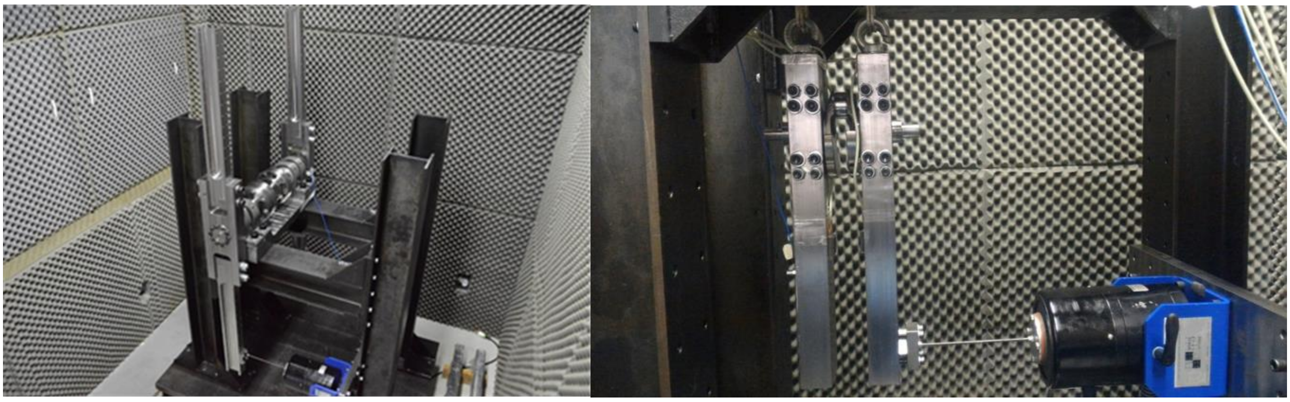

Figure 4 – Assembled bench, evidencing the torsion core (left) and the bending core (right).

The test bench was equipped with the HBM® TB2 - 5 kN.m static torque transducer. The transducer has a nominal capacity of 5 kN.m, measures alternating torque, has a precision class of 0.03 ("HBM", 2017), and an IP67 protection level (ABNT NBR IEC 60529). The chosen transducer for the sensor is the PCB Piezotronics® model 3741B1250G, which operates on direct current and has a silicone (resistive) transduction structure. The sensor has an operational acceleration range of ± 50g and a frequency range of 0-1000 Hz ("PCB Piezotronics, Inc.", 2017). The selected strain gauges for bench instrumentation were from the manufacturer Kyowa®, model KFGS-3-120-C1-11, consisting of a 3mm unidirectional grid with a nominal resistance of 120Ω.

The development of the crack propagation control and mapping system by changing the natural frequency has been discussed by Cunha et al 2022. The control system was developed using the LabVIEW® platform in combination with a National Instruments PXIe-8135 controller ("National Instruments", 2017). The control algorithm was developed using a combination of PID control and natural frequency identifier, capable of tracking the change in the system's natural frequency during the test. Frequency control is performed through frequency sweeps during the test. As shown in Figure 5, the green arrows correspond to the first natural frequency sweep, while the orange arrows correspond to sweeps performed to correct the bending moment during the test.

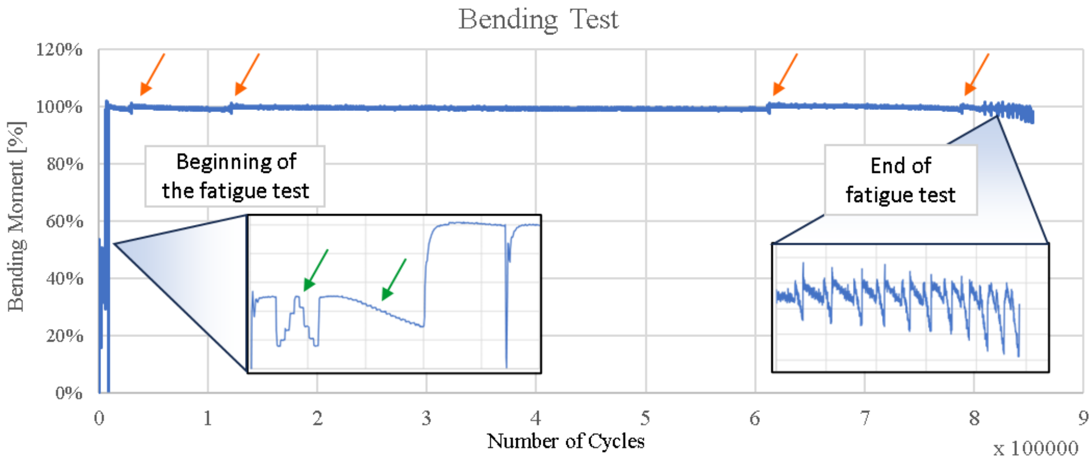

Figure 5 –Automatic behavior of the equipment analyzed from the bending moment graph along a bending test.

On the right side of Figure 5, the results related to the moment obtained at the end of the fatigue test are enlarged. A sequence of frequency sweeps can be observed within a short period. This is due to the accelerated growth of an existing crack, which drastically reduces the stiffness with each load cycle, causing the frequency sweep to be unable to keep up with the change in natural frequency. As a result, the test is interrupted, and the test specimen is evaluated for the presence of cracks. Figure 6 exhibit a specimen with cracks obtained through the use of a test bench in the research carried out by Fonseca et al. in 2019. The left side of the figure shows a crack observed in a specimen using the liquid penetrant method, while the right side shows the same specimen revealing the exposed fractured section.

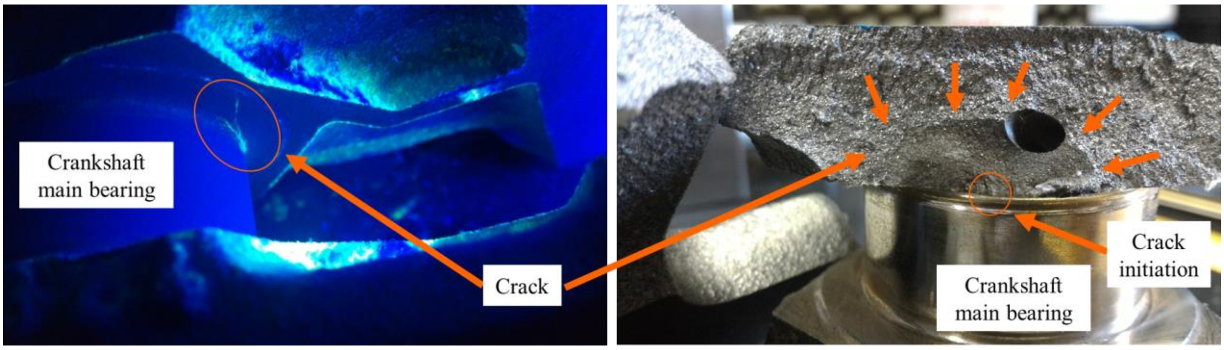

Figure 6 - Visualization of a crack by the liquid penetrant method (left) and the analysis of the fracture with the specimen open in the crack section (right).

This specimen was the result of research by Fonseca et al 2019, which consisted of a numerical model to simulate a manufacturing process and correlate with the component's fatigue strength.

As a result, there is a 100% automated shaft test bench from the beginning to the end of the fatigue test, with the specimen preparation and fixation on the test core remaining manual. The preparation time for the test specimens can be eliminated by manufacturing other fixation devices, allowing the activity to be performed in advance. For reference, the bending tests were conducted at 55 Hz, achieving a maximum duration of 50 hours, which is approximately the time to reach 10 million cycles.

4. CONCLUSION

The developed test bench demonstrated full capability to perform fatigue tests on shafts and automotive crankshafts. Bending tests were conducted with loads of up to 700 N.m at a frequency of 55 Hz, totaling over 100 million cycles. Additionally, torsion tests were carried out with loads of up to 1900 N.m at a frequency of 36 Hz. For safety reasons, the load verification was performed with gradual torque increments to avoid abrupt failures.

The Information Project stage successfully transcribed the customer's needs, providing a comprehensive understanding of the customer's actual interests in the product. Developed with the aid of the first QFD matrix, the House of Quality enabled the definition of project specifications and their respective weights, generating a robust project requirements structure for conceptual development.

The Conceptual Project stage allowed for a comprehensive functional analysis, with a detailed functional structure that unfolded into the necessary components and systems to fully meet the customer's requirements. As a result of the Conceptual Project development, the morphological matrix facilitated the generation of alternative solutions, and the best-qualified alternative solution converged on the conceptual definition of the project.

The Detailed Project stage specified and dimensioned the components and systems according to the conceptual definition. Critical components were verified through structural simulation using Ansys Workbench 18.0 software, and the results facilitated the selection of materials for manufacturing.

By comparing the product to the initially proposed scope by the client, we can confirm the success of the solution. The achieved equipment has the capability to fatigue test shaft in both low and high cycles. Its operation is extremely safe due to the automation of the testing stage. By utilizing the resonance phenomenon, the equipment has low energy consumption. The reproducibility has proven to be very satisfactory, showing a smaller deviation compared to the client's historical results. The accuracy of the input force in the system has been reduced from +/- 20 N.m (as provided by the client) to +/- 5 N.m due to the automatic correction system. The operation has been made easier, with only a few input parameters in the software, such as testing moment, approximate natural frequency, and frequency change limit. Thanks to the low energy consumption and the optional presence of an operator, the overall testing cost is dramatically reduced. Lastly, the system features automatic control of the testing load and real-time data acquisition.

5. ACKNOWLEDGEMENTS

This study was partially funded by the Brazilian agency CNPq under grants 159026/2013-0 and 147267/2015-3 and also Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) under Grant 88881.187305/2018-01 for the Programa Institucional de Bolsas de Doutorado Sanduíche no Exterior - PDSE.

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7. RESPONSIBILITY NOTICE

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