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DESIGN AND MANUFACTURE OF A TEST BENCH FOR INDUCING RESONANT REGIMES IN BEAMS OF ROTARY MACHINERY SUPPORT

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Abstract. *In this paper, a test bench projected to induce resonant regimes in a support beam is described and detailed in draws. The necessity of studying resonance effects comes up due to the fact that uncontrolled vibrations of base structures of equipment produce harmful aspects for assembly lines, beyond representing a danger to the workers. One way to study these effects is by altering the stiffness of the support by means of the geometric portion of the structural stiffness, which represents an introduction of a nonlinear geometric parameter on vibrations of rotating machinery support structures. That occurs because the dynamic characteristics of structural systems depend on their stiffness and mass. With these, the natural frequencies and modes of free vibrations can be determined. Nevertheless, the initial stiffness, computed in its unloaded state, can be affected by the applied forces, the so-called geometric stiffness. Compressive forces usually reduce the stiffness and, consequently, the frequencies of vibration, whereas tension forces elevate these same frequencies. In order to experimentally assess the previously mentioned hypothesis and induce resonant regimes, a test bench was projected and fabricated trying to approximate, at the maximum, the mathematic to the physic of the problem. In this sense, lies the biggest challenge for the project, which is to depart from the initial conception based on a determined use and goes until the materialization of the ideas. In this sense, to make possible the investigation, all parameters had to be defined in a preliminary stage of calculation for determining the weight of the engine, operation frequencies, dimensions of the cross-section, and the way by which the materialization of the boundary condition of the problem would be reached.*

Keywords: *Project, As built, Engine Base, Beam Resonance, Geometric non-linearity*

1. INTRODUCTION

It is known that the dynamic characteristics of a structure depend basically on its stiffness and mass. With these two parameters, the natural frequencies, and modes of vibration of the system are determined. However, the initial stiffness of a structure, defined in the unloaded situation, are affected by the presence of loading. This is the case for compression forces, which tend to decrease the stiffness and vibration frequencies, which may, in the limit, lead to loss of system stability, as in the case of columns, or to resonate, as occurring with vibration problems. This is also the case for tensile forces, which tend to increase the stiffness and frequencies of vibration. This latter phenomenon is explored in the so-called tensegrity structures, which work as cable-strut assemblies; their stiffness and self-equilibrium states result from the interaction of tension in cables and the compression in bars, as shown by Ashwear, Tamadapu and Eriksson (2016). Works that clarify the concept and importance of stiffness and evaluate the geometric stiffness in the vibration of mechanical systems can be found in Pauletti (2013); Wahrhaftig, Brasil, and Balthazar (2013); Wahrhaftig and Brasil (2017); Brasil and Wahrhaftig (2018); and Wahrhaftig et al. (2018).

One class of mechanical systems of importance to the national industry is the machine bases, subject to vibrations induced by the supported equipment. These vibrations can affect the safety of the structure itself, but, in the general case, can have harmful effects on the equipment itself and the quality of the manufactured product. They can also make inappropriate the environment work for the operators. Problems related to vibration of rotating machines in some field of engineering can be found in Adams (2000), Brandão (2013), Assunção (2009), Silva et al. (2016), Bachmann and Ammann (1987), Kapsalas et al. (2016), Satpal et al. (2013) and Sotiropoulos and Tsihrintzis (2016).

In order to evaluate experimentally the effect of geometric stiffness on the dynamic behavior of structures excited by periodic loads, this work describes with design details a bench specifically made for this purpose in laboratory tests.

2. SUCCINCT MENTION ON THE MATHEMATICAL BASE OF THE PROBLEM

In the context of the dynamics of structures, Figure 1 assumes that the presence of an axial force P, which decreases the beam's stiffness and consequently its natural vibration frequencies, can lead to unexpected, potentially dangerous resonant regimes. In Figure 1, L is the length of the beam, f_E, and $\omega_n(P)$ are the motor frequencies and the natural frequency of the beam, respectively, E_g designates the rotating machine and M_E your mass, EI is the product of the bending stiffness of the beam, h and t_h is the side and wall thickness dimensions of the cross-section of the beam.

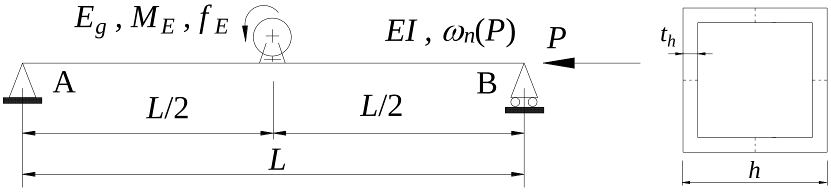


Figure 1. The mathematical hypothesis of the problem: (a) beam model, (b) cross-section.

When approaching the present problem through continuous mechanics, it is possible to obtain the frequency of the first natural mode of vibration of the beam represented in Figure 1 as a function of the compressive force P. It could be verified, mathematically, that making the force P as the independent variable of the problem and calculating the beam frequency for increasing force levels according to a small increment, as can be seen in Figure 2 the resonance is induced to a specific intensity of force (resonance force), generating a resonant regime that can be noticed by the intersection of the presented curves, black one (beam) and blue line one (rotating machine), which can represent an unwanted design condition. Therefore, as seen, it is necessary experimentally to assess that condition.

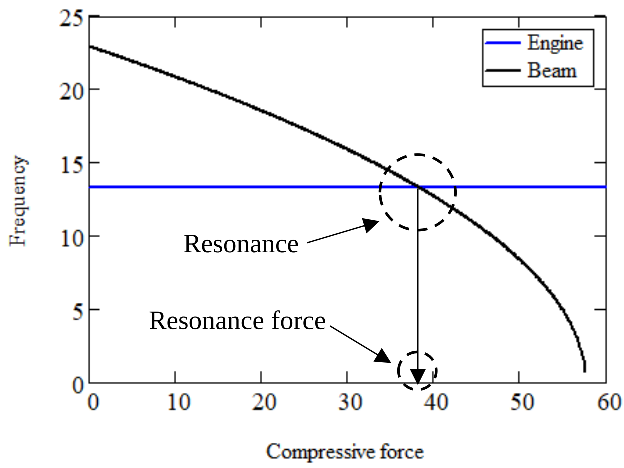


Figure 2. Resonant regimen in the structural system of base.

3. DESCRIPTION OF THE DESIGN

Analyzing the object of study in this case, the bench of tests was initially designed on sketches which made possible the definition of its pieces through laboratory tests. The difficulty inherent in this type of creation is to establish a possible relationship between the mathematical theory which is being studied and the physics of the problem, making possible the choice or definition of subsystems that mechanically behave as desired and, at the same time, would be commercially usual and relatively easy to be found or made. Thinking about that, the schemes were initially elaborated by means of simple traces, all of them freehand made, where the solution of the problem was graphically elaborated and where it was possible to visualize primarily the object to be constructed. With the problem and the solution in mind, the ideas have been thrown on paper and the first lines gave a shape to the creation, as shown in Figure 3.

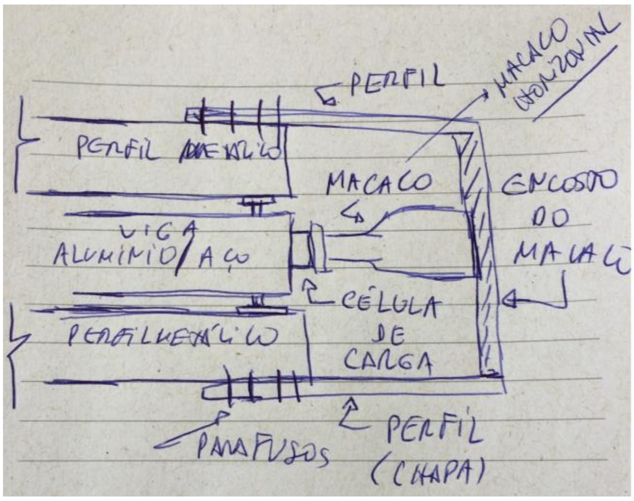


Figure 3. Design of the roller support (measurements in "mm").

Therefore, in order to investigate the hypostasis considered was designed a test bench to perform a physical test, consisting of a steel beam compressed by a hydraulic jack, supporting an engine which served as an excitation to the structural system of base (Wahrhaftig et al, 2020). When designing that system of test, different levels of the horizontal forces to be applied were predicted. The specifications of the components used in the experiment were defined, with their graphical representation and a brief description of the principal constituent elements, as follows. The model was constructed with parameters which can lead the theoretical consideration to be tested. Figure 4 and Figure 5 show the details of design of the pinned and roller supports, respectively. The former consists of a robust metallic axis with bearings on both sides, placed between short plates located above and below, and welded to a square plate fixed at the top of the beam. This prevents any horizontal and vertical motion but allows rotation. Laterally, thick plates were designed to fix this set of parts to the supporting beam by means of pins.

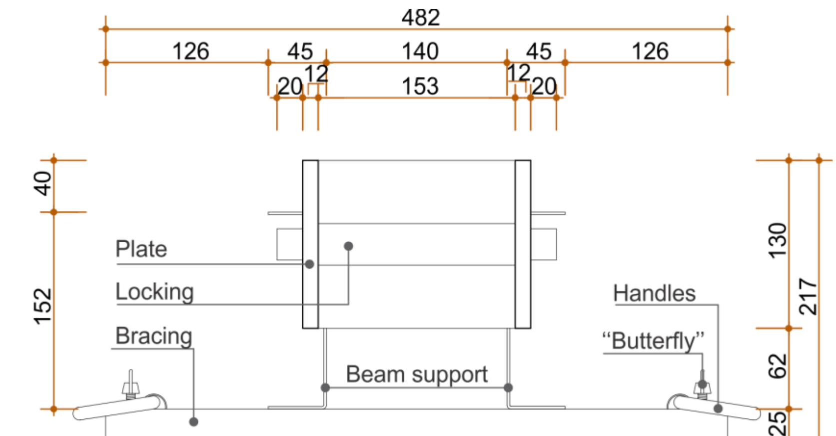


Figure 4. Design of the roller support (measurements in "mm").

The latter is similar to the former, with a bearing of smaller diameter added to the end of the axis at the point of contact with the support and inserted into a U-shaped profile segment placed laterally and facing vertically inwards. There, a limiter that eliminated the clearance between the bearing and the upper part of the U-shaped bearing was added. Thus, the roller support allows all types of motion in the plane that contains the beam axis, except for vertical motion.

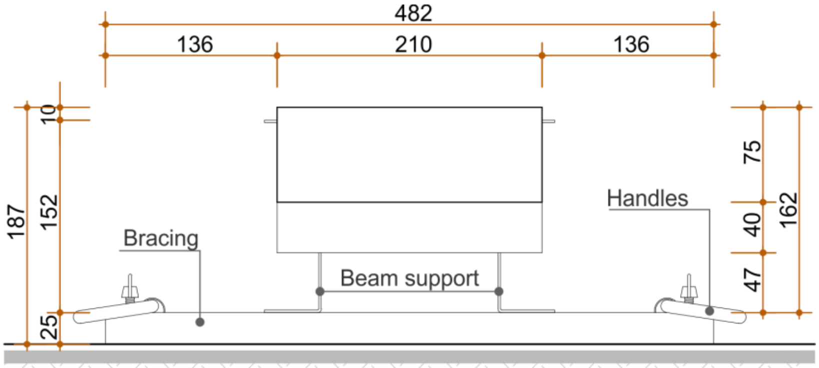


Figure 5. Design of the pined support (measurements in "mm").

Laterally, on both sides of the beam, U-shaped cold-formed metal profiles served as supports for the central steel beam. Three transverse bracings were arranged along the profiles, stiffening the system in the transverse direction. All of these stiffeners had transport handles and height variators at their extremities. The height variators were butterfly threaded screws with a small circular plate in their extremity, enabling manual adjustment of the verticality of the system. A set of metal parts formed by the union of other U-shaped profiles, arranged at the side, and flat plates, placed at the above and below, were mounted and joined by welding in order to build the support for the hydraulic jack, as illustrated in Figure 6. This assembly was built before the roller support, outside of the theoretical length of the beam. The profiles that formed this assembly were connected to the main part by screws and pins. A planar plate was placed crossing the upper face of the test bench and was welded on both sides across the U profiles, in an attempt to guarantee the safety of the researchers in the case of sudden beam failure.

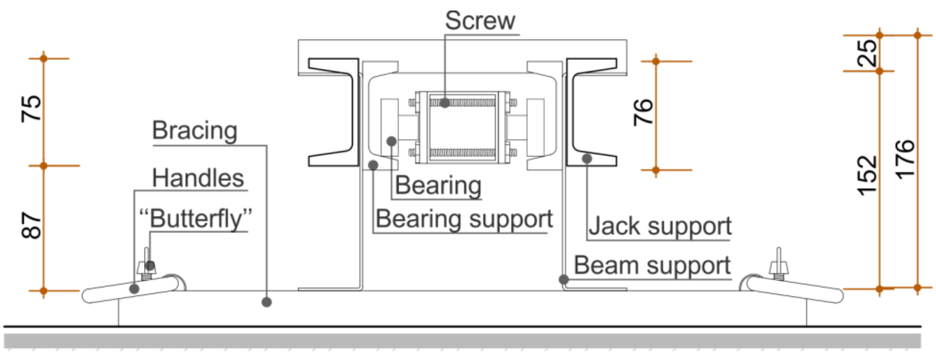


Figure 6. Cross-section of the test bench and details (measurements in "mm")

Figure 7 presents the three-dimensional views of the designed prototype. A top and lateral view that graphically illustrates the previous description can be seen in Figure 8. The assembly formed in this way was also designed to provide the desired inertial safety for the tests and had at least five times the mass of the excitation.

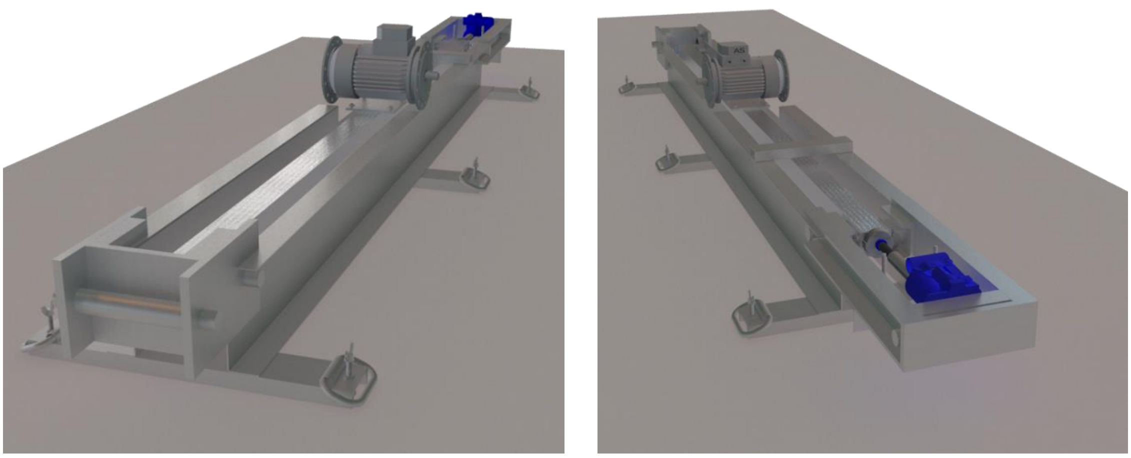
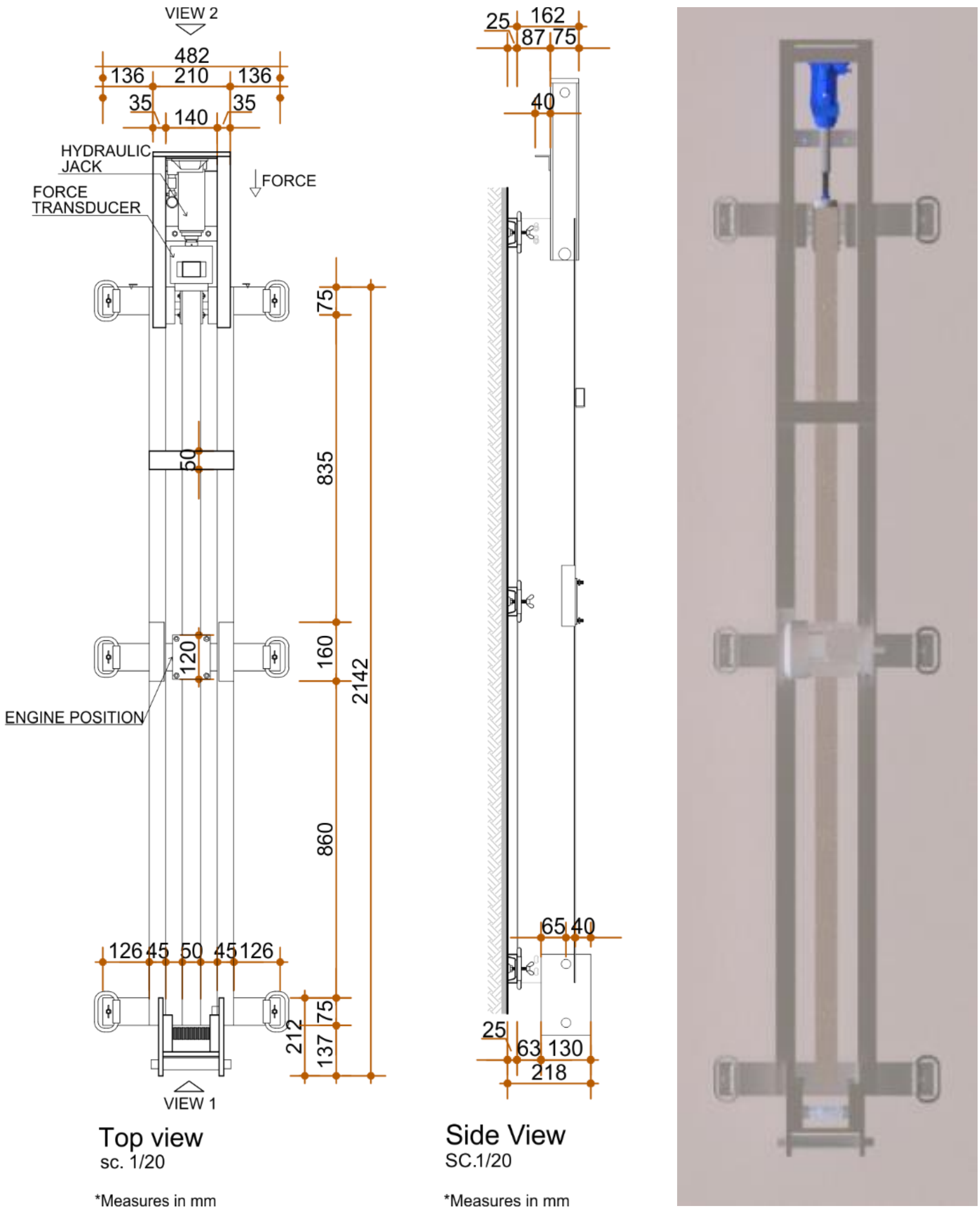


Figure 7. Isometric views.



(a) (b) (c)

Figure 8. Views: (a) top and (b) lateral (dimensions in mm); (c) rendering.

4. MANUFACTURE

The manufacture process conducted to elaboration and assemblage of each part of the test bench, such as the beam supports, transversal stiffnesses to provide operational conditions into the scientific context of investigation. Figure 10 and Figure 11 provide details of fabrication and final scheme of assemble of the pinned and roller support.

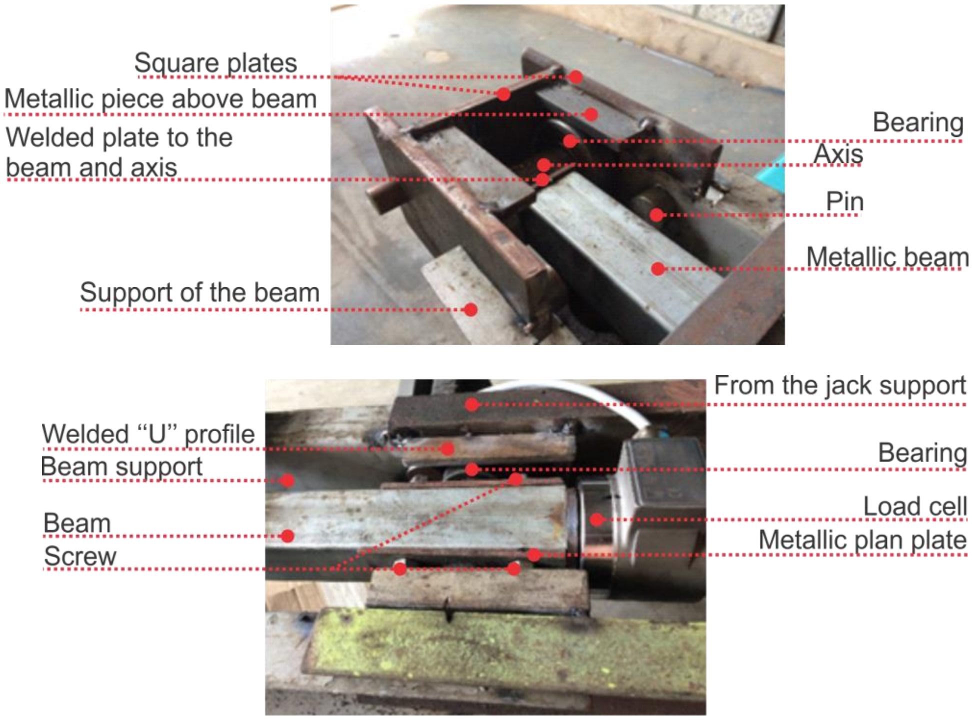


Figure 9. Detail of manufacture of the roller support.

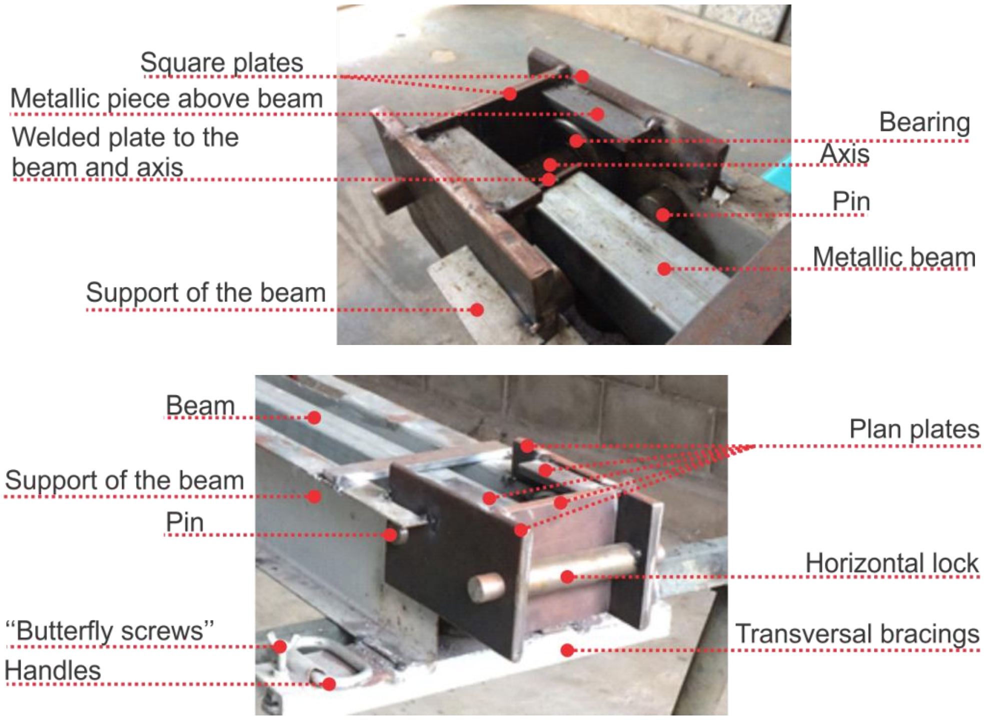
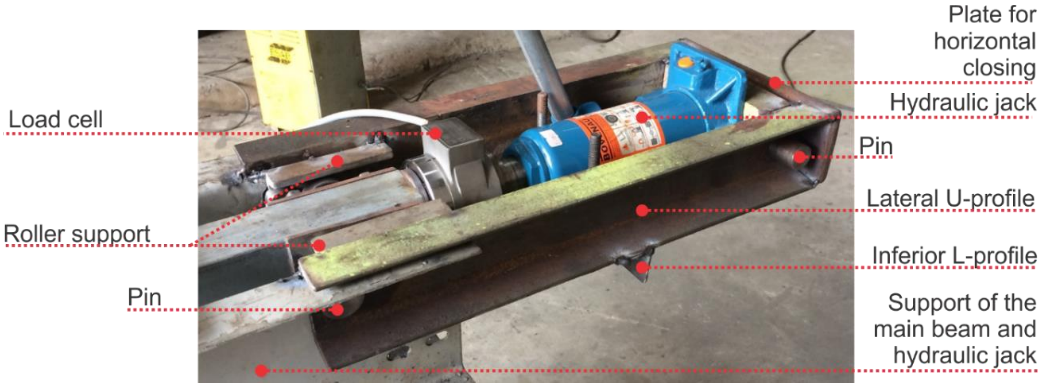
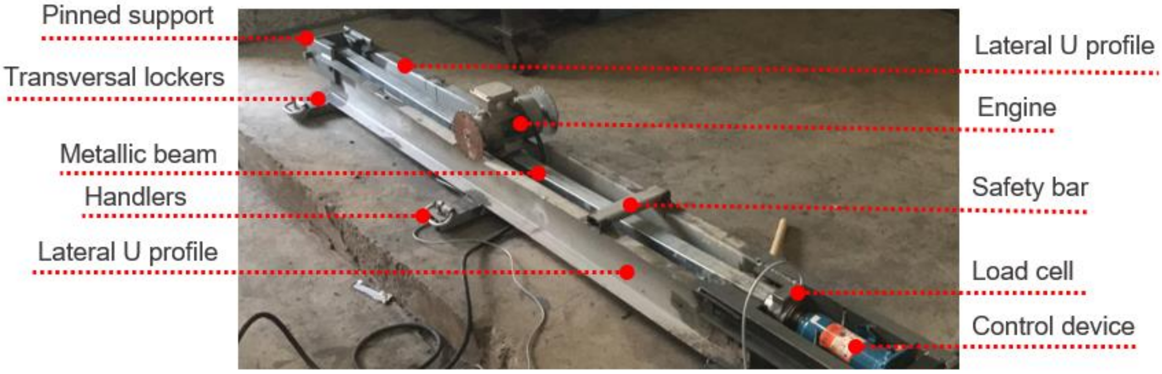


Figure 10. Detail of manufacture of the pinned support.

In turn, Figure 11 shows details of the device position responsible to apply the horizontal force and the test bench used in the experimental proof and its service conditions.



(a)



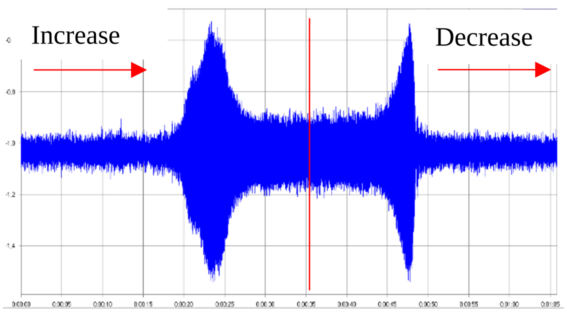
(b)

Figure 11. Photos: (a) detail of the hydraulic jack position, (b) the test bench.

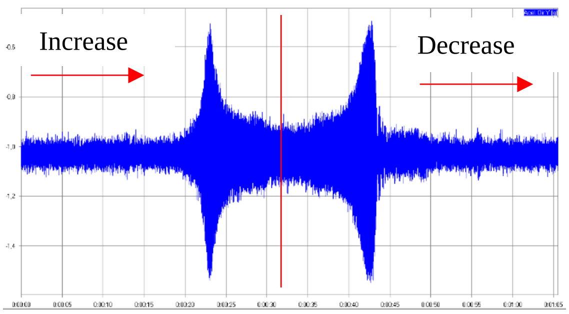
5. OPERATIONAL TEST

An instrumentation scheme was elaborated to carry out the experimental test. A frequency inverter was used to vary the engine frequency of excitation, allowing sweeping forward and backward, exciting the base system in its natural frequency. The response of the structure was acquired using an ±50 *g* accelerometer (Lynx technology, 2014), where *g* is the acceleration of gravity. The force was controlled by load cell type 1-C6A/200KN, described as a force transducer with nominal force 200 kN for compression loading (HBM, 2014). Both sensors were connected to a digital data acquisition system ADS-1800 fabricated by Lynx technology (2014), basically characterized by having universal analog switches individually configurable by software, a 24-bit A/D converter of resolution per channel, and standard communication via Ethernet network of 10/100 Mbits/s. The acquisition system was then connected to a portable microcomputer. The acquisition rate used for the experiment was 1000 Hz.

The temporal series are presented in Figure 12. There it is possible to see two stages well defined. One corresponding to the sweeping forward the frequency until the middle of the temporal series, and the second corresponding to the sweeping backward. The passage by the resonance is easily realizable by the presence of peaks in the signals. So that, as can be seen, the resonance is crossed twice, one when the frequency is going up and another when it is going down. This operational test was carried out for forces equal to 0 and 5 kN.



(a)



(b)

Figure 12. Experimental temporal series: (a) 0, and (b) 5 kN.

6. CONCLUSION

Can be concluded that the designed test bench is an appropriate device for capture resonant regimes in the structural system of base. This equipment can prepare favorable conditions for performing studies about the vibration of base structures and tools of control.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Adams, M., 2000. *Rotating machinery vibration*. Marcel Dekker, Inc. ISBN - 0-8247-0258-1.

Ashwear, N., Tamadapu, G. and Eriksson, A., 2016. *Optimization of modular tensegrity structures for high stiffness and frequency separation requirements*, International Journal of Solids and Structures 80:297–309. https://doi.org/10.1016/j.ijsolstr.2015.11.017.

Assunção, T.M.R.C., 2009. *Considerations on dynamic effects and induced loading by sources of excitations in industrial structures*, Thesis (Master), Engineering School at Federal University of Minas Gerais.

Bachmann, H. and Ammann, W., 1987. *Vibrations in Structures — Induced by Man and Machines*, Structural Engineering Documents, Vol. 3e, International Association of Bridge and Structural Engineering (IABSE), Zürich.

Brandão, A.T., 2013. *Nonlinear dynamics of rotary machines in the presence of contacts between rotor and stator*, Thesis (Master), Faculty of Technology, University of Brasilia, Brasília/DF.

Brasil, R.M.L.R.F and Wahrhaftig, A.M., 2018. *Experimental Evaluation of the Effect of Geometric Nonlinearities on Structural Resonances*. Experimental Vibration Analysis for Civil Structures. EVACES 2017. Lecture Notes in Civil Engineering, vol 5. Springer, Cham. https://doi.org/10.1007/978-3-319-67443-8_53.

HBM - Test and Measurement, 2014. User Guide and Specifications, São Paulo

Kapsalas, C.N., Sakellariou, J.S., Koustoumpardis, P.N., Aspragathos, N. A., 2016. *On the Vibration Control of a Flexible Metallic Beam Handled by an Industrial Robot Within an ARX-Based Synthetic Environment*, In: Rodić A., Borangiu T. (eds) Advances in Robot Design and Intelligent Control. RAAD, Advances in Intelligent Systems and Computing, vol 540. Springer, Cham. doi:10.1007/978-3-319-49058-8_6.

Lynx Electronic Technology, 2014. User Guide for AqDados/AqDAnalysis, São Paulo

Pauletti, R.M.O., 2013. *History, Analysis and design of tensegrity structures*. Thesis (Free Teaching) – Polytechnic School of University of São Paulo, São Paulo.

Satpal, S.B., Khandare, Y., Guha, A., et al., 2013. *Structural health monitoring of a cantilever beam using support vector machine*, International Journal of Advanced Structural Engineering 5:2. doi:10.1186/2008-6695-5-2.

Silva, J.G.S., Sieira, A.C.C.F., Silva, L.A.P.S., Rimola, B.D., 2016. *Dynamic analysis of steel platforms when subjected to mechanical equipment-induced vibrations*, Journal of Civil Engineering and Architecture 10:1103-1113, doi:10.17265/1934-7359/2016.10.003.

Sotiropoulos, D.N., Tsihrintzis, G.A., 2016. *Machine Learning, Machine Learning Paradigms*, Volume 118 of the series Intelligent Systems Reference Library, pp 9-50. doi:10.1007/978-3-319-47194-5_2.

Wahrhaftig, A.M., Brasil, R.M.L.R.F., and Balthazar, J.M., 2013. *The first frequency of cantilevered bars with geometric effect: a mathematical and experimental evaluation*. Journal of the Brazilian Society of Mechanical Sciences and Engineering 35:457–467. doi:10.1007/s40430-013-0043-9.

Wahrhaftig, A.M., and Brasil, R.M.L.R.F.., 2017. *Initial undamped resonant frequency of slender structures considering nonlinear geometric effects: the case of a 60.8 m-high mobile phone mast*. Journal of the Brazilian Society of Mechanical Sciences and Engineering. doi:10.1007/s40430-016-0547-1.

Wahrhaftig, A.M., Brasil, R.M.L.R.., and Nascimento, L.S.M.S.C., 2018. *Analytical and Mathematical Analysis of the Vibration of Structural Systems Considering Geometric Stiffness and Viscoelasticity*. Numerical Simulations in Engineering and Science, 1:349-369. https://doi.org/10.5772/intechopen.75615.

Wahrhaftig, A.M., Brasil, R.M.L.R.D.F., Groba, T.B., Rocha, L.M.L., Balthazar, J.M., and Nascimento, L.S.M.S.C., 2020. *Resonance of a rotary machine support beam considering geometric stiffness*. Journal of Theoretical and Applied Mechanics, Vol. 58(4), pp. 1023-1035. https://doi.org/10.15632/jtam-pl/126681.

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