Robotized System for Determining the Acoustic Emission

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***Abstract*—**The paper is presenting the results of a development research for a robotized application of acoustic testing, which has been developed within a research project for the improvement of the capabilities of an acoustic testing laboratory. The robot design imposed certain requirements different from the common one, such as: very low noise emission, low speed but high synchronization of the movements on the axis. The final solution was a combination of standard positioning axes, modified by the producer and a orientation system internally developed. The final test certified the capability of the robot, the system being actually in the phase of software integration with the acoustic measurement system.

***Keywords*—**Robot, Intensimetry, Acoustic Emission.

I. Introduction

THE main goal of the project whose result is presented herein was the achievement of a system – a certain type of robot, placed within an anechoic room, which will have to move in space an intensimetry probe, continuously oriented to the normal of the testing surface. This kind of robot can fulfill the measurement and/or testing conditions of the noise levels from different sources, in this way situating in space different measurement instruments, according to the stipulations of various standard procedures and methods. In accordance to the main objective of the project, the robot will have to fulfill also the conditions of the latest and most complex standard for the measurement of the acoustic intensity ISO 9614-3:2002 [1]. This standard settles an exact measurement method of the acoustic power through spatial scanning with an intensimetry probe for a scanning surface associated to the noise-generating source. According to this standard, against all the other standards, in which the measurement instrument is in repose in the measurement moment, in our case the intensimetry probe has to move continuously, with constant speed and on very precise trajectories. Those trajectories will cover through scanning all the surfaces or parts of the surfaces, who are limiting the volume surrounding an object whose noise level/acoustic power must be measured. The spatial robotized scanning covers in the same time all the requirements of some experimental researches, which have to optimize in a constructive way in order to reduce the noise emissions of certain products (domestic, production/manufacture, etc).

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II. Designing Hypothesis

According to the stipulations of the above-mentioned standard, the robot to be designed, manufactured and used within the anechoic room must fulfill two technical conditions of great difficulty:

- the designing of a 6 mobility degrees robot, who must generate scanning spatial trajectories (parallel, go and back, passing over) while it is moving with constant, programming speed, regardless the lateral surfaces types of the scanned volumes: prismatic, cylindrical or spherical. This is enforcing a very complex control program with movements and speeds interpolation, which in order to impose a constant speed on the trajectory, it must guarantee almost permanently continuous variable speeds on the coordinates axis;
- a robot whose own noise level during the operation must be 20 dB smaller than the one of the testing source/product.

Giving all these, since the designing phase of the robot a great attention was paid to the solutions of reducing to minimum of the noise generated by the actuating and guiding systems of the robot displacements. In order to assume some of them, preliminary experimental tests were performed and even real functional demos.

There were established the following designing requirements for the robot:

- the architecture upper robot structure/number of mobility degrees: cartesian/3;
- displacements on the cartesian axis: X = 1800 mm. Y = 1800 mm, Z = 1425 mm;
- the load displaced on the vertical axis (z), the weight of the orientation device of the transducer/probe + their own weight: Sz = 40,5 N;
- displacement speed and its adjustability on every axis: (0,05 … 0,5)m/s;
- the positioning precision of the reference point of the capturing surface for the orientation device: ± 0,5 mm;
- the architecture orientation device structure/number of mobility degrees (transducer/probe permanently oriented on the normal to the surface in every measurement point): polar+translation/2+1;

- displacements on the orientation device axis: φz = ± 360o ; φy = ± 90o , x = 1000 mm;
- displacement speeds: angular = 90o/s, linear = 0,5 m/s;
- the displaced load (transducer weight/probe): St = 5N;
- positioning/pursuit precision of the spatial trajectory: ± 1 mm;
- pursuit precision of the measuring surface normal: ± 2o;
- the guidance and control of the robot: programming;
- the settlement of the measuring volume for its scanned surfaces and parts of surfaces: through software;
- the control of the measurements, the recording and processing of the data, the elaboration of the measurements/tests report: through software;
- the printing of the measurements/tests report: on the printing machine;
- the pursuit of the spatial measuring process, in the (imposed) absence of the human factor in the anechoic room: with the help of a video camera;
- the noise "target" level = minimum 50-55 dB.

This last requirement is not common for robotics and the experimental tests were very discouraging, so it has been imposed a "target" limit, with solutions for the entire designing, some of them constructive essentially, in order to decrease the noise at a minimum possible level.

The technical data of the designing theme are leading to a robot loaded with small and medium values forces on the cartesian axis, but with a large operating volume – very large displacement range.

The fastening possibilities of the robot are not allowed to be on the floor (there are measurement standards where the floor does not exist, remaining a metallic network instead, directly above the soundproof cubes) but only at the ceiling level (covered also with soundproof cubes).

At the floor level, incorporated within, there is a metallic table, with its own vibration-proof foundation, where are placed the testing products. The table has the following sizes:1990 x 820 mm. The large displacement ranges (curse) on the X and Y axis are expelling the fastening of the robot directly on the table. These displacement ranges are leading to over 2400 mm of total lengths of the units and to a great potential of unbalance for the table in certain spatial positions of the robot.

It is also worth to mention that in the anechoic room of the laboratory will take place many noise tests, some of them excluding any kind of equipment in the room, even the robot. This thing is imposing a great vigilance in the designing because the entire robot, its holder and the fastening elements, all of them must be assembled and disassembled very easy and precise.

In accordance to the final solution of the robot (the detailed settlement is presented further), this solution has the configuration from the Fig. 1, where it is reproduced a spatial representation of the robot, conceived and designed through computer in Solid Works program, 2004 version. Fig. 2 is presenting a sketch of the orientation system of the intensimetry probe.

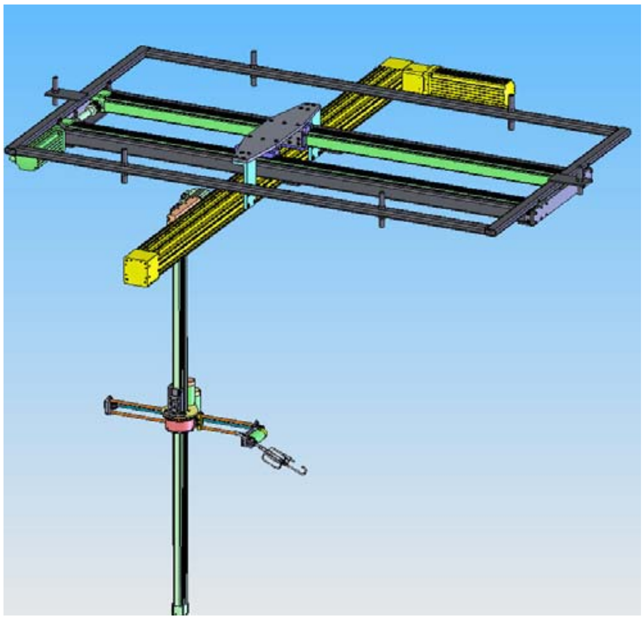

Fig. 1 Full design of the robot

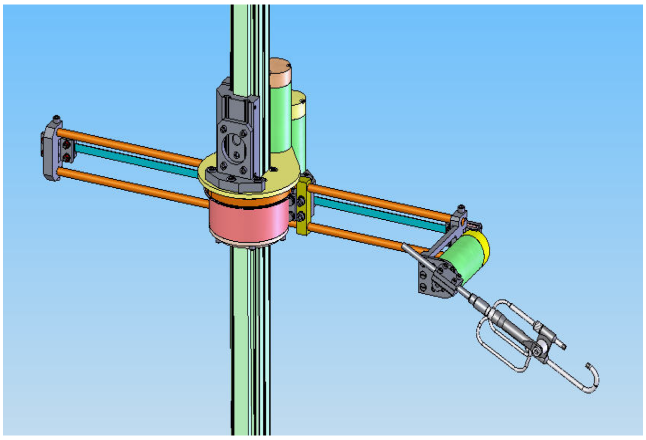

Fig. 2 Detail of the orientation subsystem design

III. Translation Subsystem X-Y-Z

From the constructive point of view, almost all the robots are realized through a combination of rotation or translation units. This thing has encouraged the producers to design and manufacture positioning modular units, capable to architecture the robots in any kind of coordinates axis system: cartesian, cylindrical or spherical. The essential elements in selecting positioning units are the weight of the handled object, the displacement speed, the positioning precision and the working range. All these technical features are founded in the production catalogues of the companies who manufacture robots and precision operations. Giving the fact that there was no such requirement until present day, nowhere in the world is any reference about the "noise level" parameter, the most important parameter for the robot from this project.

The final solution decided was to buy some units with potentially reduced or reducible noise level through technical solutions. It came only natural the acquisition of certain modular units of translation for the large displacement ranges and in correspondence with XYZ, the cartesian structure of the robot's body.

Regarding the materialization of the necessary mobility degrees for the orientation device of the intensimetry probe (φ_z, φ_y and x), which can be fasten and positioned at the translation mobile table of the X axis unit and knowing that there are no driving units for the necessary parameters, it was decided the entire design and manufacture of this device.

The placement of the robot in the anechoic room in order to reduce its noise level (this being the target itself) has imposed the adoption of a controlling and driving solution of the robot from outside the room. In this way, regardless of the driving type – electrical, hydraulic or pneumatic, only the orientation engines will be placed on the robot, the most favorable being the hydraulic and pneumatic ones – the cylinders, who are directly and in very good conditions producing the translation displacements. There are no modular units with linear electrical engines, for the required technical performances. In such conditions, all the control and supply equipments of the energy necessary for the engines must be placed outside the anechoic room.

With the same purpose – to reduce the noise during the measurements, there is no human driver in the anechoic room and the computer who runs the operating and controlling program for the computer is outside the room. To observe the robot process of operating inside the room, there are two video cameras, both joined to a second computer monitor, which is outside the anechoic room.

From the noise levels point of view, the hydraulic displacements are naturally the most noiseless ones. Then follow the pneumatic and electrical displacements. The electrical ones have a rotating electric engine, no matter if it is step-by-step or continuous, DC or AC and represents the main noise source. This being the real situation for these types of operations, the final option is the electrical operation, the reasons sustaining this choice being the following:

- for the hydraulic operation – the hydraulic energy generating group has a very high noise level and thus, its presence in the room next to the anechoic room is not allowable. The link between the regulation equipments of the output and pressure (the balanced distributor and the servo-valve) around 6m long is causing delays, delays which are negatively influencing the displacement control. The flexible range of the hoses, who must charge the cylinders and who fills different positions in space, is representing a very difficult problem – solving it with a guiding chain is not possible because of the additional noise made by the chain.
- for the pneumatic operation - although they have lower precisions (the servo-distributors and servo-valves do not exist in this case), the supply and control equipments of the pneumatic cylinders are very noisy (the pneumatic valves controlled by modular impulses are known for this disadvantage). The 6 m distance is reducing the displacements control possibilities because the termogasodynamic operations are very fast in the pneumatic mode and the 0.5m/s speed or even smaller cannot be granted, as the standard stipulates for certain situations.

Analyzing the situations last mentioned results that the electrical operation is the only solution possible. The electrical option has its advantages: the control and drive is operating with the same energy source, the orders and charges of the engines are made from bigger distances, it is compatible with the computer driving, the ranges of the electrical circuits are more convenient and the link window between the two rooms has the smallest sizes.

The adoption of technical and constructive solutions in order to reduce its own noise becomes a permanent task. From this point of view, from the many choices to manufacture the modular units with electrical operation, it has been outlined the following technical conclusions:

- among the displacement and entrapment solutions of the translation table, screw with balls or serrated belt, although the last one is assuring smaller operating forces, the serrated belt is the choice;
- among the guiding solutions for the table, rolling or sliding bearings, the sliding bearings are the choice (the pneumatic units from Festo company have this kind of bearings);
- among the guiding solutions, rolling bearings with re-circulating balls or reels on rubber trails, the last ones are worth to mention that the forces and the moments tolerated by the bearings are small, even at the biggest typo-dimension; if the designing calculations are correct, then the guiding reels with rubber are the choice.

Following some functional demonstrations where the noise emission was measured, demonstrations made for many positioning units from well-known companies, the conclusion was that at the electrical operation units, the metallic balls guiding is significantly contributing to the noise generation; this means that it is a bigger noise source than the engine itself and the reducers. The reels units with rubber, although noiseless, have small allowable charges and thus, they are expelled since the resistance calculations phase of the robot. The only noiseless units are those with sliding bearings, but only few companies manufacture them. Unfortunately, they have pneumatic operation. A very important criterion takes into consideration in the final selection was the supplier availability to modify the structure of the positioning axis by making a hybrid.

With a view to lower at minimum the noise made by the robot during measurements and in agreement with the Festo GmbH company, it was decided to modify (for the first time) the main units with electrical operation that are configuring the robot's body (X,Y,Z). Understanding the necessity of noiseless robots in the future, the company has agreed to replace the rolling balls guiding, typical for the electrical operation units, with sliding bearings guiding, specific for the pneumatic operation units.

The very short time available to manufacture such special operation units has leaded to the following agreement (knowing that the manufacture of the other robot's components was depending on their manufacturing): after their delivery, the functional test have to be made together with the company representatives, in the anechoic room - the place where the robot was sitting in order to measure the noise levels during the displacement.

The experiments made for every unit typo-dimension ("25" for Z axis, "40" for X axis and "63" for Y axis) have the following targets:

a) functional behavior, with standard driving and controlling program of the electrical units with rolling balls guiding, having in mind that the manufactured guiding with sliding bearings have bigger friction forces, but much noiseless;

b) the achievement of speed components in the interest speed field ≤ 0,5 m/s (exactly as the standard is imposing), knowing that at small speed (specific for the sliding bearings) appears the blocking-sliding phenomenon, wherefrom is resulting discontinuous displacements (forbidden by the standard). The possible field of these units speeds specified in the catalogue is (0,2…10)m/s;

c) the stop precision at a fix/programmed point; in the catalogue it is guaranteed a ± 0,1 mm error for the electrical operation units;

d) the displacement precision and dynamic in the reverse points of displacement drifts, in the case of a continuous and repeated back and forth operation;

e) the measurement of the noise level for every unit, in different drives regimes and displacement speeds, but especially for the one with maximum drives, with continuous reverse of the displacement drift and relative small speeds ≤ 0,5 m/s (the scanning trajectories are imposing this, as the standard says).

Regarding the last-mentioned experiments, the following results have been obtained:

- the criterion from a) – the electronic controllers of every unit were accelerated by the electrical units driving program. Although these controllers have been modified in the mechanical area – sliding guides instead of rolling guides, the program was compatible.

- the criterion from b) – they have been programmed and achieved speeds of (0,2…3)m/s. The blocking-sliding phenomenon did not appear at small speed because the possible driving forces reported to the necessary forces were oversized, even thou the friction forces in the sliding bearings of the guides are bigger:

- on X axis – a double unit with unique synchronic operation, with "40" profile: the necessary force for the structure calculation F_{nec} = 116 N < F_{pos} = 610 N;

- on Y axis – one unit with "63" profile: the necessary force for the structure calculation F_{nec} = 28 N <<F_{pos} = 1500 N;

- on Z axis – one unit with "25" profile: the necessary force for the structure calculation F_{nec} = 40N <F_{pos} = 260 N.

From the robot architecture in Fig. 1, we can see that only the Z unit translation table is directly loaded with the orientation device weight of the intensimetry probe, which will have to be placed on it. At x and Y axis, the weights are taken over by the caissons of "63" and "40" profiles. The profiles are very intense required at twisting and bending and they need such dimensions. For the X axis the situation was delicate – in order to resist to the pressure, the Y axis was upheld (and in this way, the entire weight of the robot) on two translation units, putted in parallel (a very demanding solution in the assembling phase, when the parallelism must be assured).and simultaneously operating by a single electrical engine. The duplex assembly of such translation units is common for the company involved, similar solutions being frequent for the robots with cartesian coordinates, like this one.

- the criterion from c) – less important for the way the robot is evolving related to the exact standard procedures, continuously and constantly moving, with all the units corresponding the precision positioning – errors in ± 0,1 mm domain. During the experiments, it has been followed the way the controller is adjusting the speed variation through negative accelerations, very important aspect for responding to a procedure. It is imposing that the passing from a scanning trajectory to the next one (where the displacement drift is reversed) to be made with constant speed. The achievement of the positioning precisions is a very good indicator of the speed control. In order to insure the proper function of this condition, it must prove efficient when the units are operating the robot and the constant aped condition results from the speed interpolation, adjusted simultaneously from at least two axis.

- the criterion from d) – even if they have been made on every axis unit individually, the simulation of an interpolation being impossible, they have been closer to the robot operating way – reverse direction displacements. The field for the spreading of the turning points at the necessary 0,5 m/s speeds is good: ± 1 mm, allowable in the procedures. At very high speeds, the more pronounced dynamic of the moving tables has produced larger fields of ± 2,5 mm (3 m/s speed). As the fore-mentioned observations from c), the interpolation and its results remains a very important problem, taking into consideration the real operating conditions of the entire robot.

- the criterion from e) – the purpose was to measure the noise level of every unit. In order to obtain good results, it has been interfered in the standard architecture of the units: they have been made sliding bearings guides instead of rolling bearings. Beside this solution, there is no other to contribute to the noise reduction.

In the table below there are the values of the measured noise levels in the anechoic room for every unit, in a continuous back and forth displacement on the maximum working drift, at four speed values (0,2m/s, 0,3m/s, 0,4m/s, 0,5m/s):

TABLE I

Robot axis	Typo – dimension	Noise level [dB] V=0,2 m/s	V=0,3 m/s	V=0,4 m/s	V=0,5 m/s
X	40	48	48	49	49
Y	63	47	48	49	49
Z	25	46	46	47	47

Although it has the caisson and the translation tables smaller, the X axis has a noise level almost equal to the Y axis (the biggest) because of the its composition – two parallel "40" structures.

As we have seen before, the electrical operating units, who are materializing the X, Y and Z axis of the robot's body have been bought from the FESTO company in Germany. In the Fig. 3, it is presented the robot's configuration, with its structure corresponding to the three basic axes.

Fig. 3 Assembly of the x-y-z system

IV. SPATIAL ORIENTATION SUBSYSTEM

The orientation device plays an important role – to orient in a 3D space the measurement instrument of the noise level or the acoustic power, its weight being maximum 1 daN. It is assuming the translation displacement of the table on Z axis, where it is the basic fastening and is materializing around it its first mobility degree - φ_z turning around it. A framed construction with a very good bearing makes the transition of the Z axis table through it, and on the outside there is plane surface which allow the assembling of a guiding translation micro-unit, made from two rectified cylindrical rods and sliding sockets. The third mobility degree of the orientation device is realized by a rotation axis - φ_y, fasten on the translation micro-unit, being materialized by an electrical micro-engine. On this electrical micro-engine, it is fasten the intensimetry probe. All three mobility degrees of the orientation device are operated by DC electrical micro-engines. In order to be as noiseless as possible, the displacements remittance is made with serrated rubber belts. The spatial orientation device of the intensimetry probe with three mobility degrees R, φ_z, φ_y, which is fasten by the translation table of Z axis, was conceived and manufactured within the laboratory. The Fig. 4 is presenting this subsystem that is placed on the vertical axis of translation.

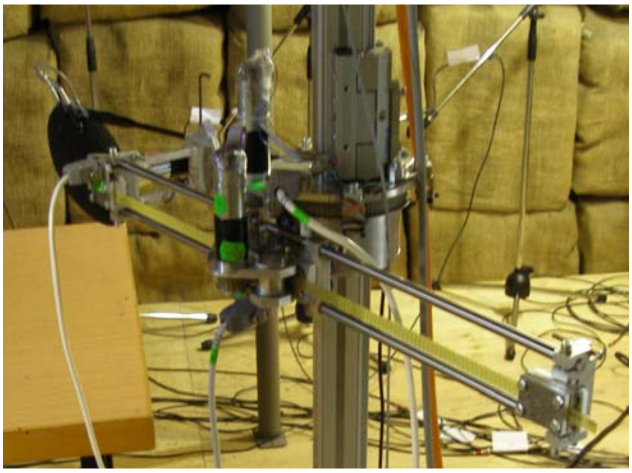

Fig. 4 Assembly of the orientation subsystem

The final assembly of the robot, placed and functional in the anechoic room, is presented in Fig. 5. According to the standard procedures of the exact operating method, during the measurements in the anechoic room there is only the robot and the source, which noise level is investigated. All other equipments – controllers, supply sources, computer are in a neighbor room. The communication between the robot, the supply systems and the control is made through cables; these cables are passing through the anechoic room by a special pipe placed in the separation wall of the two rooms and is soundproofed.

Fig. 5 Final assembly of the robot

The connection between two video cameras and a computer, on whose monitor is followed the robot's evolution, is made the same way.

As we can see, removable assemblies make the entire structure of the robot. This solution was necessary because in the anechoic room are in progress to be accredit many testing, which do not allow the robot's presence in the room. This means that the robot must be periodical dismountable and stored. The dismounting will be made at subassembly level – translation axis and orientation device, but with no interference at the initial X axis assembly, which is structured on its own metallic frame.

The control system of the robot is made for:

- the x-y-z translation subsystem, using the controllers from Festo company, joined into a CAN network and controlled through a NI-CAN board;
- the spatial orientation subsystem of the intensimetry probe, using a specialized DSP control board, NI 3744; the command is made using a vector control of the displacement in order to follow the trajectories development and respecting the speed demands;
- a software application developed in LabVIEW, that is interacting with the Festo controllers programming application and with the control application of the spatial orientation subsystem.

V. CONCLUSION

The paper is presenting a robotized application of an acoustical intensity probe for measuring the acoustical intensity and generating the acoustical emission map, using a continuous displacement in the same time with the spatial orientation. The system has imposed atypical designing conditions, where the noise reduction and the displacement control are much more severe than the mechanical resistance requirements, both in static and dynamic regime. The robotized system was manufactured and functionally validated, being right now in the phase of software integration with the acoustic measurement system.

REFERENCES

[1] ***, "ISO 9614-3:2002 Acoustics -- Determination of sound power levels of noise sources using sound intensity -- Part 3: Precision method for measurement by scanning" , ISO Standards, 2003.