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STASI (SEISMIC ACCELEROMETERS CALIBRATION SYSTEM)

Aldo Renato Terrusi [1], *Renzo Romagnoli* [2], *Roberto Silvestro* [3], *Domenico Ianniello*[4]

[1] ENEA C.R. Casaccia, Roma, Italy, email: aldo.terrusi@enea.it
[2] ENEA C.R. Casaccia, Roma, Italy, email: renzo.romagnoli@enea.it
[3] ENEA C.R. Casaccia, Roma, Italy, email: roberto.silvestro@enea.it
[4] ENEA C.R. Casaccia, Roma, Italy, email: domenico.ianniello@enea.it

Abstract – This paper present a new instrument named STASI (Seismic and Accelerometers Calibration System) invented and patented by Aldo Renato Terrusi of ENEA - Italian Agency for New Technologies, Energy and Environment (patent n° RM2004A000147,3-22-2004). This paper is a brief overview on the state of the art at international level, describing and comparing the general characteristics and costs of the instruments in relation with what is currently available on the world market. The modifications on the STASI prototype were made after the I.N.RI.M.'s comments and the experimental tests performed by ENEA Casaccia Metrology Laboratories (SIT Center n° 10), which showed an improvement to reliability, calibration's uncertainty of and the ease of use.

Keywords : seismic, accelerometer, calibration

1. STATE OF THE ART

The systems typically used by international accredited laboratories to calibrate accelerometers and seismometers are vibrators and shakers that have limits to work under 5 Hz with an acceleration like 10 ms^{-2} (approximately 1g). In order to overcome to the inherent lack of mechanical vibrators, systems to linear transfer with variable magnetic field were studied and developed. These ones being excellent equipments, but they have size limits. For example, linear systems, because of their features, should be extended beyond 10 meters to produce 10 ms^{-2} to 0,2 Hz. For this reason, these systems are extremely complex and their construction should also be supported by sophisticated monitoring systems so that the costs would grow exponentially, making virtually impossible the commercialization.

To overcome the shortage peak to peak displacement of traditional electromagnetic vibrators, has been studied, designed and built by German Institute of Metrology (PTB) a linear transfer system (over 2 meters long) with a variable magnetic field. This sysyem allows the calibration of accelerometers to a minimum of 0,5 Hz to 10 ms^{-2}, with a cost higher than 500.000 euro; a considerable cost must be added to purchase the indispensable laser interferometry equipment.

Linear Translation Systems for the accelerometers calibration, whose peak to peak displacement is about 40 cm and that can calibrate accelerometers to 10 ms^{-2} at a frequency of 1 Hz, are today on the international market at the price of approximately 40.000 euro plus the laser interferometry costs.

Currently, at the I.N.RI.M. (National Institute for Metrological Research) in Turin, it's possible to calibrate accelerometers up to a minimum of almost 5 Hz at 10 ms^{-2}.

As in most of the international metrological institutes, such as Japan, France, England and the United States, the calibrate range for an acceleration at about 10 ms^{-2}, is hardly less than 1 Hz.

STASI System (Fig.1) is the only instrument in the world that, with low size and cost (approximately around 30.000 Euro), is able to calibrate accelerometers on three decades of frequency (from 0,01 Hz to 10 Hz) with an acceleration of 10 ms^{-2}. Being an absolute calibration system, based on the local gravitational acceleration and an inclinometer, it does not need of standard accelerometers or laser interferometry.

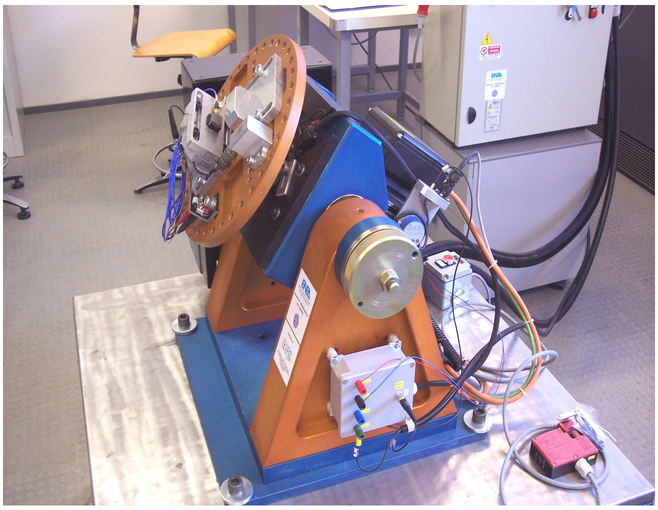

Fig.1 – STASI System.

The diagram in Fig.2 (Normogram), where are related acceleration, speed and displacement parameters depending by the frequency, shows at a glance the STASI System work's area compared with the Calibration Laboratories and International Metrological Institutes standard areas. On the abscissa there is the frequency (Hz) and the engine rotation speed (0,6 to 600 rpm) while on the order there is the acceleration (ms^{-2}). The STASI working area is enclosed in the dotted lines from 0,01 Hz to 10 Hz and from 1 ms^{-2} to 10 ms^{-2}.

The modern linear calibration systems working standard area (low frequency) is roughly enclosed in the dotted lines from 0,5 Hz to 10 Hz and 0,8 ms^{-2} ÷ 50 ms^{-2}. Extending the working area to lower frequencies (0,01 Hz) the two areas overlap partially between 1 and 10 Hz, allowing to calibrate accelerometers and seismometers at 10 ms^{-2} and allowing a continuous coverage throughout the entire frequency band. In this way STASI is an effective support to the other equipments in the calibration metrological laboratories.

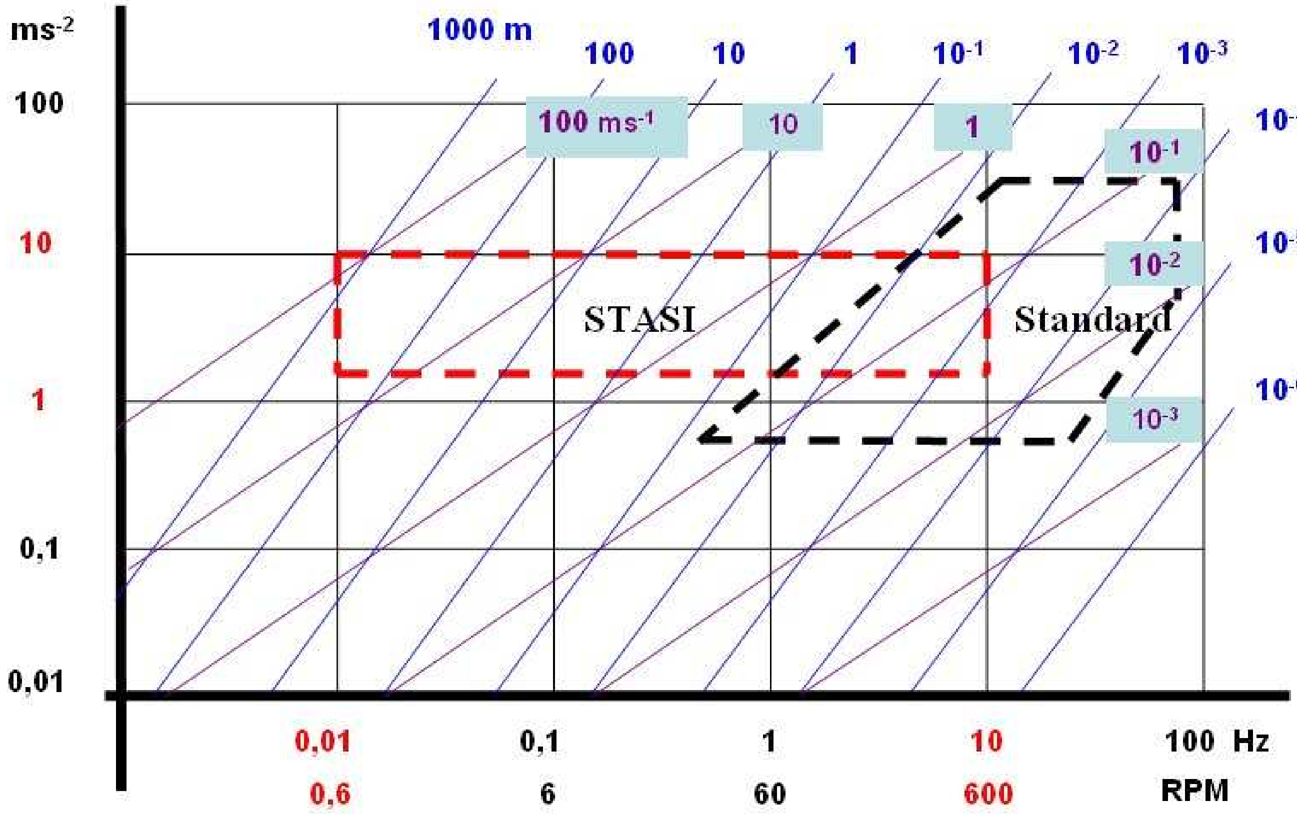

Fig.2 – Normogram.

2. SYSTEM DESCRIPTION

STASI System (Fig.3) is essentially a swinging engine (M1), which moves a turntable on which the under test sensor is placed. The main calibration stages, controlled by proper software installed on the control unit's, PC are:

- check of the proper functioning of the supply power station, by reading its control signals;
- engine inclination command (M2) and reading of the inclinometer signal;
- plate rotation command and reading of the resolver current speed;
- acquisition of the under test's sensor signal;
- processing of the acquired signals and issuance of the calibration certificate.

The command sent to the three-phase asynchronous engine (M2) to the M1's inclination control, is proportional and hence it rotates much faster as the angle to be achieved is farthest. The engine (M2) has 0,55 kW of power, a 1080 of reduction ratio (1,6 rpm) and is driven by an inverter Siemens Micromaster 420. Near the desired angle, the speed is drastically reduced to achieve 0,1 degrees of accuracy. The current angle is read by the inclinometer (I) Seika NG4U, whose main features are:

- range measurement ± 80°;
- resolution 0,01°
- sensitivity 25 mV/°

The inclinometer signal is sent to an acquisition channel by a National Instrument PCI-4474 into the PC, whose main features are:

- resolution 24-bit
- max sampling frequency 102,4 kS/s
- sampling frequency accuracy $\pm 25 \cdot 10^{-6}$

When the desired inclination angle is ready, a signal is sent to the engine (M1) speed unit control by a serial line

RS-485 according to the Modbus protocol, with this operating sequence: sending and repetition of the speed reading command up to $(SpeedSet - SpeedCurrent) < 2\%$. To switch from one speed to another and to avoid shocks on the under test sensor, acceleration/deceleration ramps are provided. The engine (M1) is a Brushless 3 kW to 8 poles and 1 000 rpm, controlled by an inverter Type Gefran SIEI driven by a digital encoder, keyed on the rotation axis which is mounted on the turntable with a 36 cm diameter with semiautomatic balance. The payload signals are transmitted to the control system by a 6 contact gold strips form Mod. B6-2 by Michigan Scientific, keyed on the M1 rotation axis. When the plate has reached its cruising speed, the sensor under test signal is acquired by a board PCI-4474 channel, as previously described. The sampling frequency is proportional to the rotation speed according to the report $Fc = Fr \cdot 2048/4$, where Fc is the sampling rate and Fr is the plate rotation frequency. The constant 2 048 indicates the total points number of a single acquisition and the constant 4 represents the period numbers during the acquisition. The engine's support structure, entirely made of aluminium, is assembled by bolts. All the transactions are made by a very functional and intuitive user interface, which allows the driver to look to the whole operation on a monitor, from the inclusion of the component under test data to the calibration certificate print.

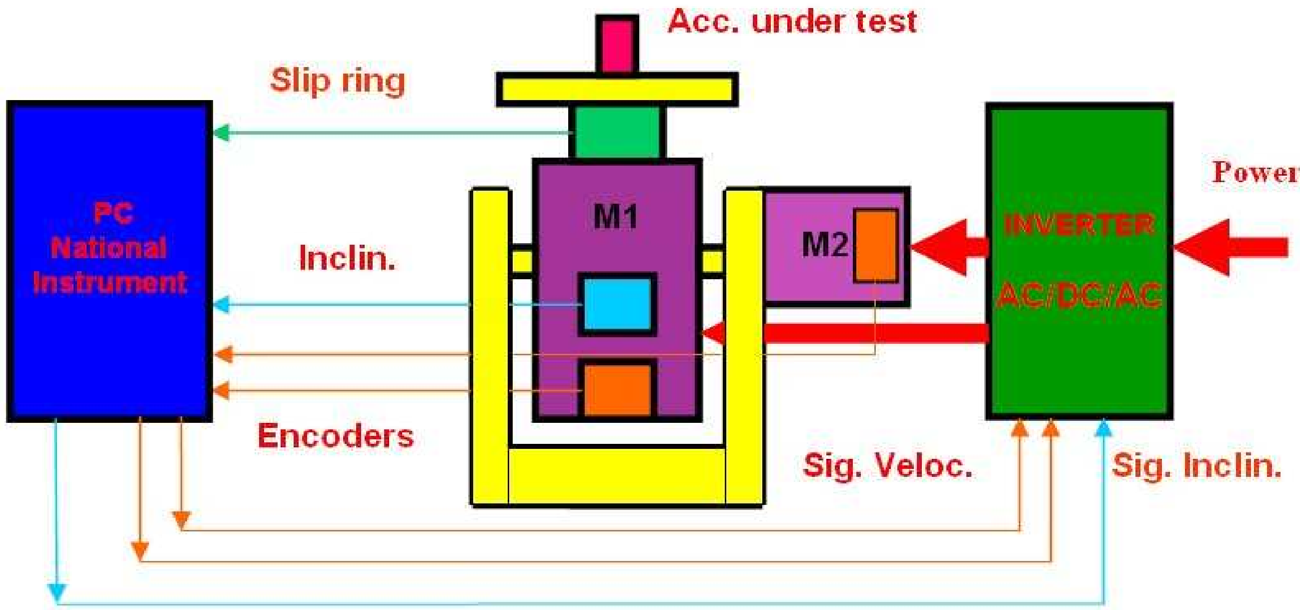

Fig.3 – STASI Pattern.

3. SYSTEM CHARACTERIZATION

For its characterization, the STASI is like a "black box", having a sine signal input from a Hewlett Packard's wave generator, which simulates the accelerometric chain signal. The sine signal has been set to 10 mV, 100 mV and 1000 mV amplitude (typical accelerometers signals output) and from 0,01 Hz to 10 Hz frequencies. The RMS signal has been measured by the STASI control software in the entire frequency range and by a HP multimeter 3458A only on the range 1 Hz ÷ 10 Hz (the multimeter is not able to measure below 1 Hz), where calculated the percentage related Waste as:

$$Waste = 100 \cdot \frac{V_{RMS(STASI)} - V_{RMS(3458A)}}{V_{RMS(STASI)}} \quad (1)$$

With these values and only for the range 1 Hz ÷ 10 Hz, the contribution to the uncertainty $u(board)/V_{RMS}$, due to the acquisition board and to the software, has been determined, whose value is calculated as an average litter divided by $\sqrt{3}$ (assuming a rectangular deviation type distribution) is 0,2%. It can be considered with good approximation that this value is valid in all frequency range 0,01 Hz ÷ 10 Hz, basing either on HP's signal generator accuracy and stability, or on the results obtained from measurements taken by the STASI in 0,01 Hz ÷ 1 Hz (compatible with those obtained in 1 Hz ÷ 10 Hz). The strip contacts introduce further contribute to the uncertainty, $u(contacts)/V_{RMS}$, which has not been experimentally determinated yet; however, basing on using experience of the high quality contact strips, it is possible to conclude that the $u(contacts)/V_{RMS}$ is never > 0,2%. The quadratic sum of $u(board)/V_{RMS}$ and $u(contacts)/V_{RMS}$ is the contribution to the uncertainty introduced by the STASI on the chain accelerometric output signal $u(V_{RMS})/V_{RMS} = 0{,}3\%$. The sensitivity of an accelerometric chain calibrated with the STASI is:

$$S = \frac{V_{RMS} + \delta_{Ripet} + \delta_{Riprod}}{g \cdot sen\alpha} \quad (2)$$

where:

- $g \cdot sen\alpha$ is the excitement acceleration generated by the STASI
- $g = 9{,}80665$ ms^{-2} is the local gravity, with negligible uncertainty
- α is the plate inclination angle, which introduces the $u(sen\alpha)$ uncertainty
- V_{RMS} is the RMS chain output signal measured by the STASI
- δ_{Ripet} is the output signal correction due to the accelerometer repeatability, with zero average value and uncertainty $u(\delta_{Ripet})$
- δ_{Riprod} is the output signal correction due to the accelerometer reproducibility, with zero average value and uncertainty $u(\delta_{Riprod})$

The relative expanded uncertainty associated to the sensitivity measures is given by:

$$\frac{U(S)}{S} = k \cdot \sqrt{\left(\frac{u(V_{RMS})}{V_{RMS}}\right)^2 + \left(\frac{u(sen\alpha)}{sen\alpha}\right)^2 + \left(\frac{u(\delta_{Ripet})}{V_{RMS}}\right)^2 + \left(\frac{u(\delta_{Riprod})}{V_{RMS}}\right)^2} \qquad (3)$$

where the coverage factor is $k = 2$ (which for a normal distribution corresponds to a coverage probability of approximately 95%), the first two terms are the contributions to the uncertainty generated by the STASI and the other two terms are the contributions to the uncertainty due to the chain accelerometric. The uncertainty associated to the α measure is ± 0,05°, determined by repeatability and reproducibility plate inclination angle measures and by the measurement inclinometer uncertainty ± 0,01°. In Table 1 is reported the STASI contribution to uncertainty calculated for various acceleration values (expressed as percentage of g):

$$\sqrt{\left(\frac{u(V_{RMS})}{V_{RMS}}\right)^2 + \left(\frac{u(sen\alpha)}{sen\alpha}\right)^2} \qquad (4)$$

Table 1 – Contributions to the STASI uncertainty.

α	Acceleration	$u(V_{RMS})/V_{RMS} = 0{,}3\%$	$u(sen\alpha)/sen\alpha$	$U(STASI)$
90,00°	100%	0,30%	0,00%	0,30%
75,00°	97%	0,30%	0,03%	0,30%
60,00°	87%	0,30%	0,06%	0,30%
45,00°	71%	0,30%	0,10%	0,30%
30,00°	50%	0,30%	0,17%	0,30%
25,00°	42%	0,30%	0,22%	0,40%

4. SEISMIC ACCELEROMETER MEASUREMENTS

Using a seismic accelerometer, sensitivity measures were carried out with acceleration excitation 9,806 65 ms^{-2} (1 g, α = 90°), in the range frequency 0,01 Hz ÷ 10 Hz. The average of the sensitivity detected values is compatible with what is stated on the calibration certificate.

Using the same seismic accelerometer, sensitivity measures were carried out ranging the excitement acceleration amplitude, maintaining constant the frequency.

In particular, the frequency measurements were made to 5 Hz, by ranging the amplitude between approximately 10 ms^{-2} (α = 90°) to 4 ms^{-2}, achieving a change in the sensitivity values = 0,2%.

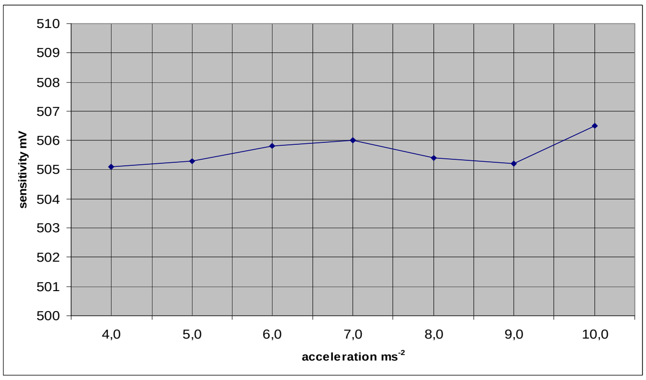

Fig.4 – Seismic accelerometer measurements.

5. MEASUREMENTS BY STASI SYSTEM AND BRUEL & KJAER SYSTEM

Three different kinds of accelerometers (capacitive, ICP, piezoelectric) were tested. The amplitude of the excitation signal was fixed at 1 g, the frequency was varied in the working interval of the STASI system and of Bruel & Kjaer system (8 Hz ÷ 3000 Hz). The B&K system was completed by a reference accelerometer B&K 8305S. Results of these tests are reported in Table 2, where the frequency of 8 Hz is in the working range of both the systems. Again, the percentage difference between the measured sensitivities is compatible with the composed uncertainty of the two systems. This uncertainty is obtained through the quadratic sum of the typical uncertainty of B&K system (al least 0,5%) and of the STASI system.

Table 2 – Measurements by STASI system and Bruel & Kjaer system.

System	Frequency	Sensitivity		
	[Hz]	Capacitive [mV/g]	ICP [mV/g]	Piezoelectric [mV/g]
STASI	0,05	990,02		
	0,10	989,73	25,20	
	0,25	989,24	62,88	
	0,50	989,43	85,23	194,02
	1	989,33	94,84	657,00
	2	989,63	97,73	956,64
	3	990,41	98,64	985,21
	4	994,14	99,07	995,78
	5	988,95	98,70	991,97
	6	987,87	98,83	995,48
	7	987,08	98,98	992,56
	8	989,24	98,86	992,13
Bruel & Kjaer	8	988,26	98,44	972,51
	10	989,83	98,35	969,38
	20	989,44	98,40	979,81
	40	988,95	98,56	977,80
	60	998,27	98,49	967,62
	100	1020,44	98,21	961,94
	200		98,63	959,72
	500		98,57	942,18
	1000		98,41	945,03
	2000		99,42	944,92
	3000		104,63	963,11

6. CONCLUSIONS

STASI is an instrument suitable to carry out acceleration chain's measures in the frequency range 0,01 Hz to 10 Hz, with an acceleration range between 1 ms^{-2} and 10 ms^{-2}.

The contribution to the calibration uncertainty introduced by STASI is the one reported in Table 1 related on the plate inclination angle, which is the excitement acceleration. Moreover with STASI is possible:

- to calibrate transducers to the 0 frequency, which are able to measure constant acceleration simply by tilting the plate;

- to calibrate transducers able to measure constant acceleration increasing the centrifugal acceleration, putting the plate in horizontal (α = 0°), placing the sensitive axis accelerometer in radial direction with its barycentre to a note distance from the rotation center and setting the plate rotation frequency.

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