SPERIMENTAZIONE DI STRUTTURE AEROSPAZIALI
TESTING OF AEROSPACE STRUCTURES

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Trascrizione e figure a cura di Roberta Cumbo

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Capitolo 1

Environmental Testing

Main objectives are:

1. check the capabilities of the system to withstand the vibro-acoustic loading during the launch
2. check the structural integrity of the system (and subsystems) after launch

The different phases are:

- modal survey
- static loads
- sine vibration test
- random and acoustic test (actual verifications of 1 and 2 objectives)
- shock qualification (for stage release)
- sine vibration test (to check structural modifications from shifts in the peaks of resonance)

1.1 How to obtain the reference PSD profile

1. Evaluation of the PSD of vibrations transmitted by the launcher to the system (known by the launcher manufacturer)

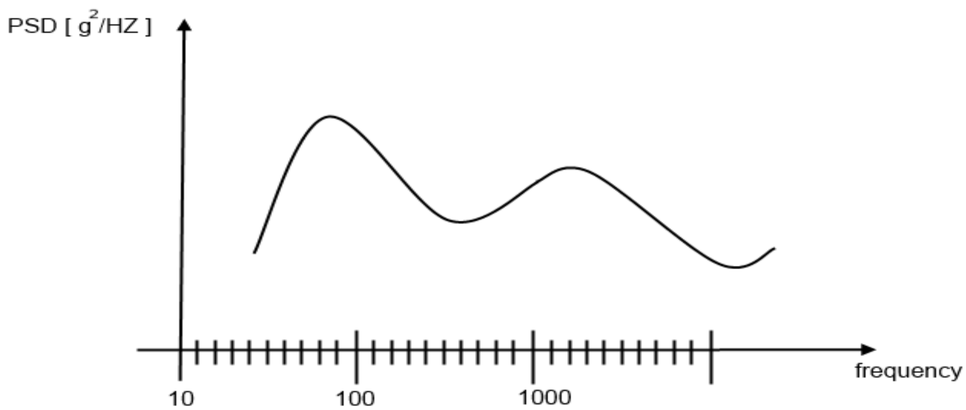

Figura 1.1

2. Calculation of the system's response to the vibro-acoustic environment:
    - lower frequency: Nastran
    - medium/high frequency: SEA

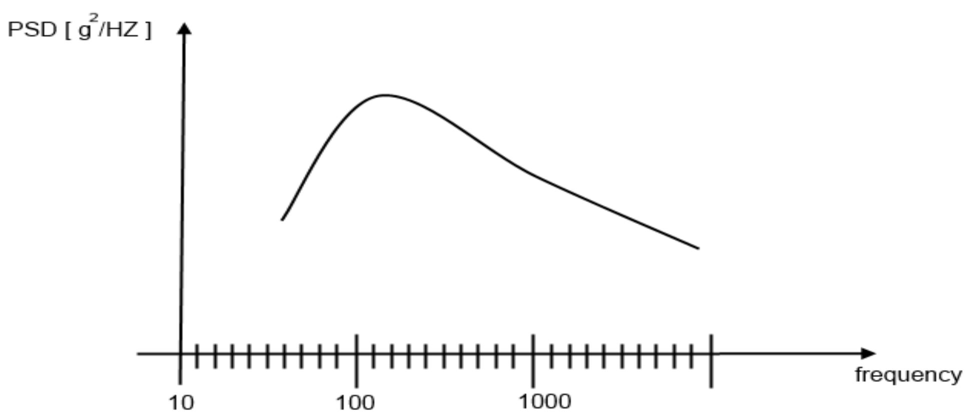

Figura 1.2

3. evaluation of the minimum vibration levels required for the identification of possible manufacturing faults (especially for electronics)

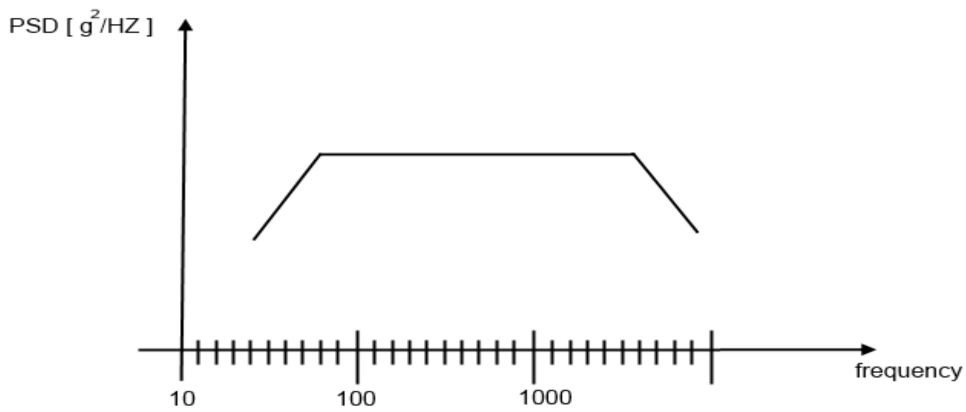

Figura 1.3

4. all the previous curves are joined together to obtain one specific spectra excitation curve: acceptance test level

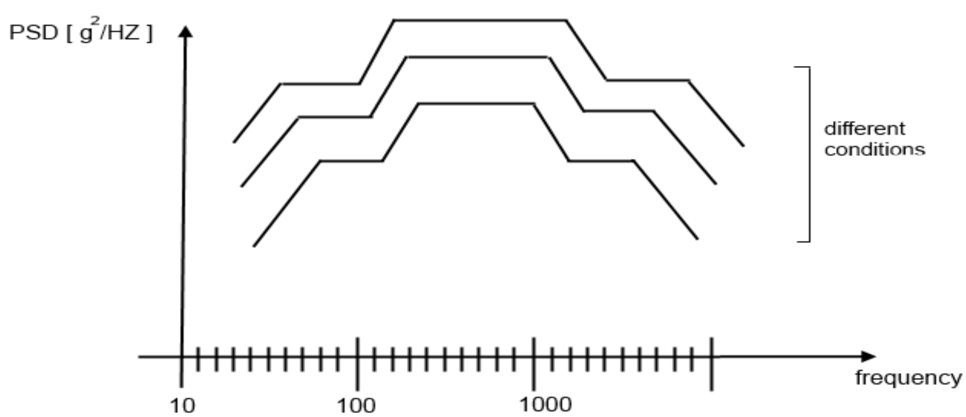

Figura 1.4

5. the acceptance spectra, increased by 3-6 dB, gives the **qualification and protoflight test levels** (safety margins are verified)

1.2 Component of typical vibration test system

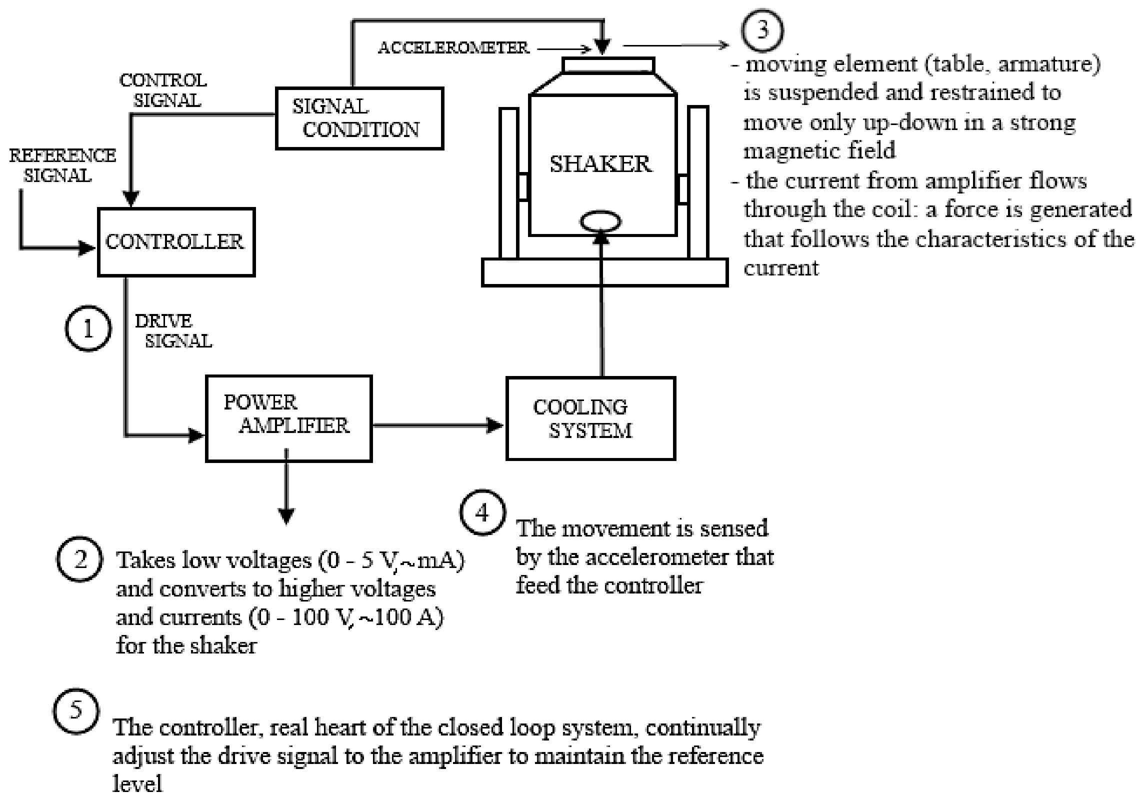

Figura 1.5

Capitolo 2

Sine Control System

- Test articles are subjected to sinusoidal accelerations using specified **acceleration levels**, while the frequency of the sine waveform is being swept from some starting frequency to ending frequency at specified rate:

  - **linear sweep**: $f(t_i) = f_i = \frac{s}{60} T_i$ ovvero $\delta f_i = \frac{s}{60} \Delta t$
    s: sweep rate in octave/minute [Hz/min]
    $\Delta t = \Delta T_{acq} + \Delta T_{proc}$: time taken to process the information

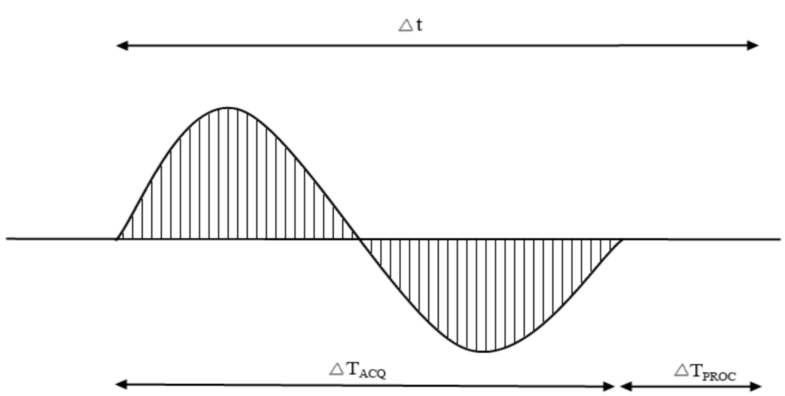

Figura 2.1

  - logarithmic sweep: $f(t) = f_0 2^{st/60}$ ovvero $\Delta f_i = \frac{s \ln 2}{60} f_0 \Delta t_i 2^{\frac{st}{60}}$
    f_0: start frequency

$f(t)$: frequency at time t

This causes the various structural resonances can be excited when the sine wave passes through the resonant frequencies.

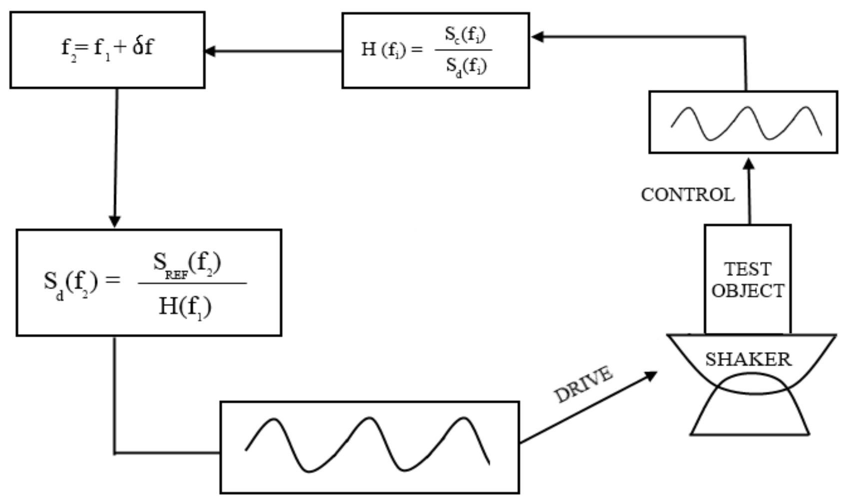

Figura 2.2: Sine control algorithm

S_c: control signal
S_d: drive signal
$H(f_i) = \frac{A_c(f_i)}{A_d(f_i)}$: control loop transfer function

If the control signal $A_c(f_i)$ differs (slightly) from the prescribed reference value, then the drive signal $S_d(f_{i+1})$ for the next frequency need to be updated such that:

$$A_d(f_{i+1}) = \frac{A_{REF}(f_{i+1})}{H(f_i)}$$

Purpose of the control system: maintaining the behavior of selected "control"point(s), either singly or in combination, at predetermined levels independent of the response of the structure at resonance.

Control algorithm performs two very important functions:

1. Shape the drive spectrum such that excitation of the control transducer(s) match a pre-defined level
2. Verify that test structure is not in danger and if it is, shut down the test

- The **reference profile levels** for various frequencies are determined by engineer test to satisfy the particular test requirements
- Typically, the levels are chosen to approximate those that will be encountered during service

2.1 Amplitude Estimators used in Sine Tests

1. **PEAK**: simply look for the maximum amplitude of the sample time signal. It is so useful for very noisy responses

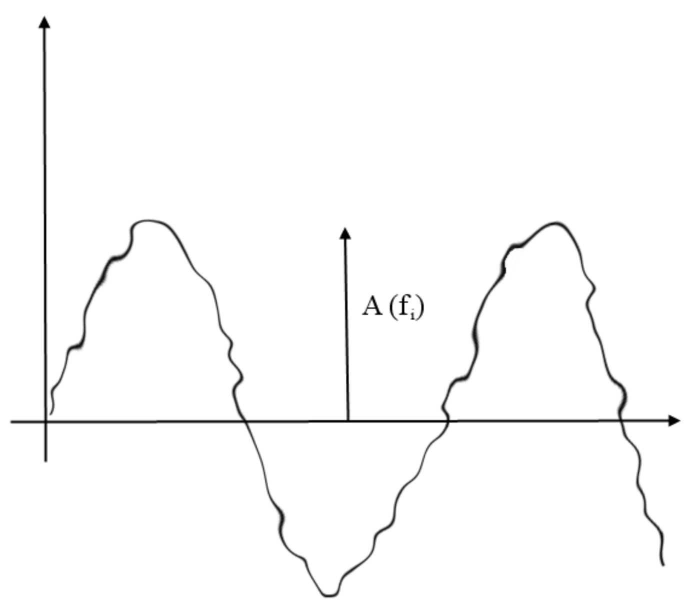

Figura 2.3

2. **RMS**: average of the squared values of all (N) time samples available in one period

$$A(f_i) = \sqrt{2}\sqrt{\frac{1}{N}\sum_{j=1}^{N} a_j^2}$$

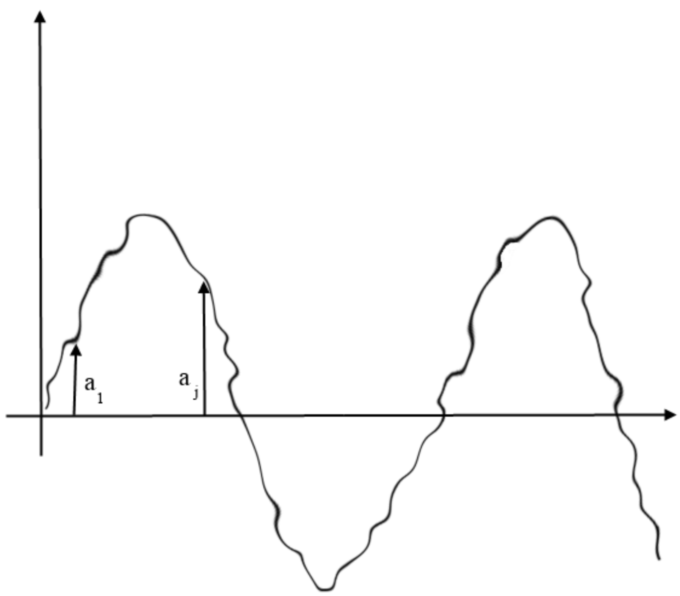

Figura 2.4

This average is then multiplied by the factor $\sqrt{2}$, which is the ratio of the PEAK to the RMS value for a pure sine wave. This method filters out the effect of quickly changing PEAK values and takes into account the complete signal, including the fundamental signal and its harmonics (in a non-linear structure case).

3. **AVERAGE**: $A(f_i) = \frac{\pi}{2}\frac{1}{N}\sum_{j=1}^{N} |a_j|$
in which $\frac{\pi}{2}$ is the ratio of the PEAK to average value for a pure sine wave, while $\frac{1}{N}\sum_{j=1}^{N} |a_j|$ means that the average of the absolute values of all (N) time sample is available for one period.

4. **HARMONIC**:

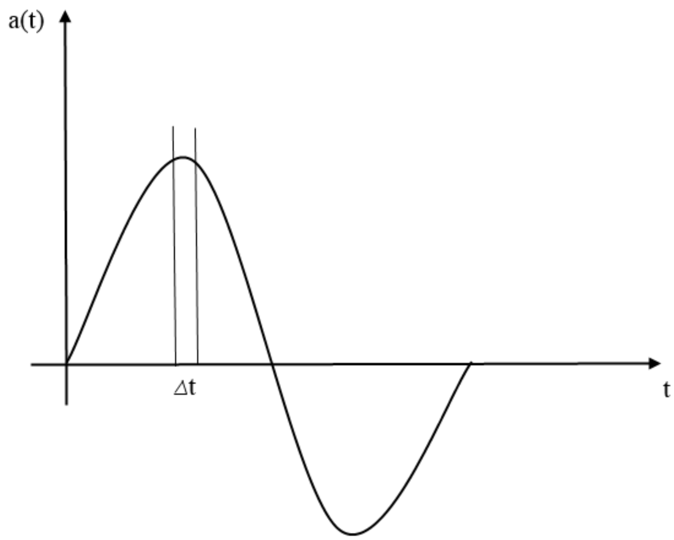

Figura 2.5

$$a(t) = a_c \cos \omega_i t + a_s \sin \omega_i t$$

$$A(\omega_i) = \sqrt{a_c^2 + a_s^2}$$

Since we are not dealing with a continuous function $a(t)$:

$$\begin{bmatrix} a(\Delta t) \\ \vdots \\ a(i\Delta t) \\ \vdots \\ a(N\Delta t) \end{bmatrix} = \begin{bmatrix} \cos \omega_j \Delta t & \sin \omega_j \Delta t \\ \vdots & \vdots \\ \cos i\omega_j \Delta t & \sin i\omega_j \Delta t \\ \vdots & \vdots \\ \cos N\omega_j \Delta t & \sin N\omega_j \Delta t \end{bmatrix} \begin{Bmatrix} a_c \\ a_s \end{Bmatrix} \tag{2.1}$$

and for a signal composed of n frequencies:

$$\begin{bmatrix} a(\Delta t) \\ \vdots \\ a(i\Delta t) \\ \vdots \\ a(N\Delta t) \end{bmatrix} = \begin{bmatrix} \cos \omega_1 \Delta t \sin \omega_1 \Delta t & \cdots & \cos \omega_n \Delta t \sin \omega_n \Delta t \\ \vdots & \vdots & \\ \cos i\omega_1 \Delta t \sin i\omega_1 \Delta t & \cdots & \cos i\omega_n \Delta t \sin i\omega_n \Delta t \\ \vdots & \vdots & \\ \cos N\omega_1 \Delta t \sin N\omega_1 \Delta t & \cdots & \cos N\omega_n \Delta t \sin N\omega_n \Delta t \end{bmatrix} \begin{Bmatrix} a_{c1} \\ a_{s1} \\ \vdots \\ a_{cN} \\ a_{sN} \end{Bmatrix} \tag{2.2}$$

is solved used a least squared error techniques to obtain the best estimates for a_c, a_s; $A(\omega_i)$ is calculated using a_c and a_s

- to be used when noise or harmonics should be filtered out as much as possible
- this technique is the only that provides both amplitude and phase

Capitolo 3

Random Vibration Test

- Test articles subjected to random accelerations in a specified frequency range (20-2000 Hz)
- This causes the system to response as it would be excited during the launch phase
- The system must withstand the dynamic excitation without damages
- Control is exercised by measuring Power Spectral Densities (PSD) and comparing to PSD reference
- Test procedure:
  - test object excited following the prescribed (reference) shape of PSD in 20-20000 Hz (typical)
  - test object excited along three axis

INNER LOOP: a number of PSDs are acquired and averaged from each control channel then a single "PSD control"is calculated and averaged with previous ones. This PSD is checked for abort and alarm conditions. Before transfer function is calculated, a new drive level computed and sent to amplifer/shaker.

- **Acquire time samples:** parameters refer to min/max frequencies and frequency resolution

- **Compute average PSD:** obtain an average control PSD. Factors are averages per loop (number of times the inner loop will be executed)

$$\bar{G}_i = \bar{G}_{i-1} + \frac{G_i - \bar{G}_{i-1}}{i}$$

$\bar{G}_i$: actual average value
G_i: current value
$\bar{G}_{i-1}$: previous average value
i: average counter

If higher the number of averages taken and more accurate the PSD, will cause a longer and less responsive control loop.

- **Update control PSD:** the control spectrum of previous stages is not directly used for drive calculation. Instead, a weighted sum of the current value and the value from the precious loop is used.
Control is exponential average in time to allow the control system to be responsive to the most recent changes in the behavior of the external load without taking the risk of divergence of the control signal from drive signal due to:

  - random measurement errors
  - short disturbances occurring during a single loop

$$\bar{G}_{j+1} = \bar{G}_j + \frac{G_{j+1} - \bar{G}_j}{W}$$

j: control loop count
$\bar{G}_{j+1}$: current averaged control PSD
$\bar{G}_j$: previous averaged control PSD
G_{j+1}: current estimate of the control PSD
W: exponential weighting factor (low W: response loop more responsive to changes; high W: more importance is given to previous values)

- **Compute the inverse transfer function:** if no abort condition exist, current drive is exponentially averaged with the accumulated drive of previous loop. Then the amplifier/shaker/test object chain transfer function is recomputed from the "average control

PSD"and the new exponentially "average PSD of drive signal":

$$\frac{1}{|H|} = \sqrt{\frac{G_{xx}}{G_{yy}}}$$

The magnitude of the new transfer function is used with reference PSD ($|S_r|$) to generate an updated drive $|S_x| = \frac{|S_r|}{|H|}$ given the magnitude of the drive signal $|S_x|$, the controller must generate a corresponding time domain waveform.

- **Send out drive signal:**
  1. the controller must generate time domain waveform
  2. the amplitude distribution of the time signal must be gaussian
  3. a random phase is associated with each magnitude (0-360Â°) - Central Unit theorem
  4. this spectrum is then inverse Fourier Transformed in time domain

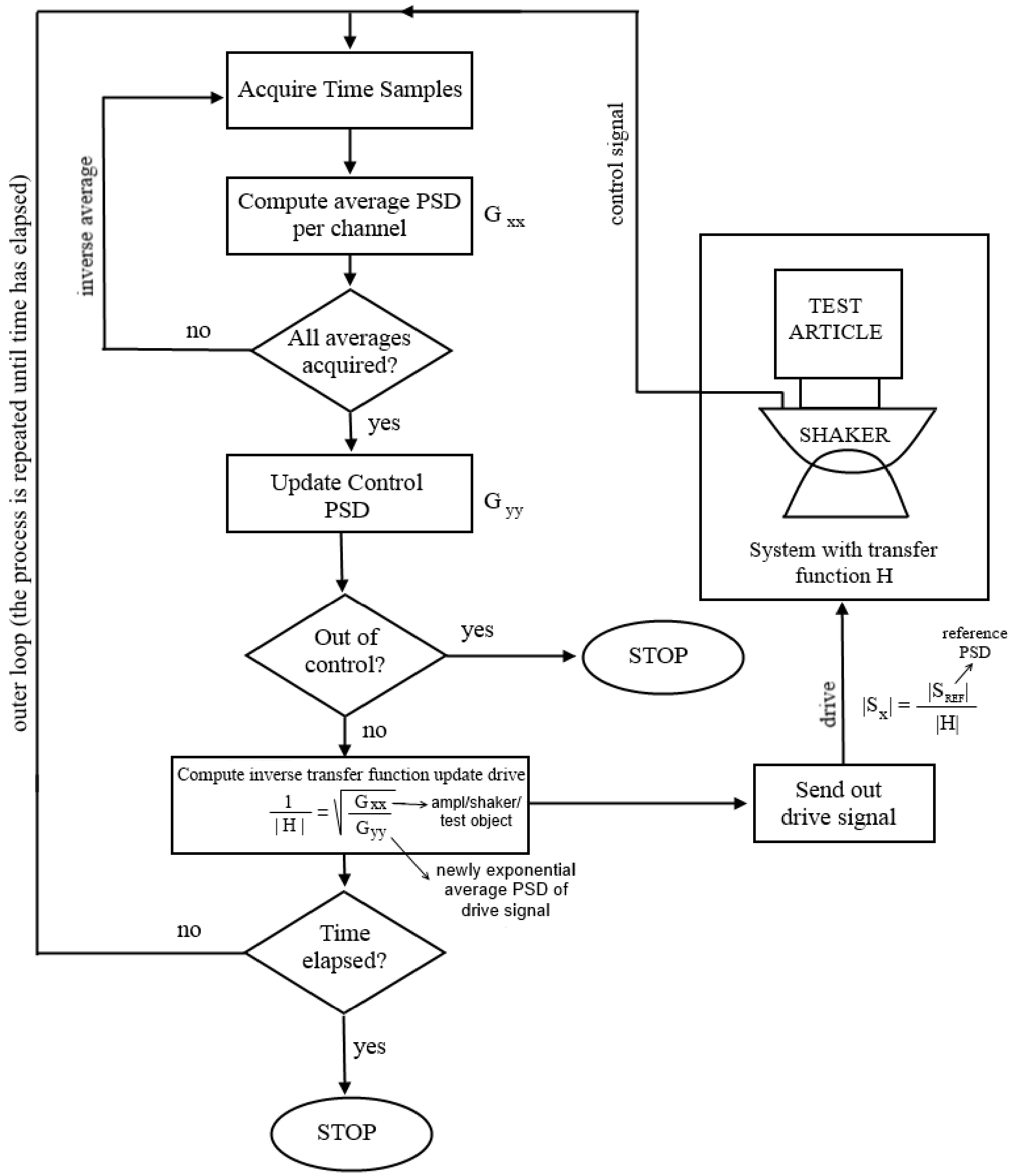

Figura 3.1: Inner Loop

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[2] Christian Lalanne, Mechanical Vibration and Shock Analysis, Vol. 5, 2nd Ed.