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(54) Title: METHOD AND SYSTEM FOR CLAMPING FORCE ESTIMATION

(57) **Abstract:** The present application discloses a method and respective system for estimating the clamping force required by each fastener element in a joint system, based on the vibration generated by dynamic loads. The method now proposed is comprised by two stages. In a first stage, a first resonance frequency of the joint is measured. In the second stage, the joint is subjected to vibration at the first resonance frequency - obtained from the first stage - in sinusoidal mode to estimate the force and acceleration of each joint. This method is based on vibration analysis to determine the local mass, and consequently the local dynamic force applied to a fastener element when subject to external loads, and can be applied for joints made of different materials consisting various number of joints.

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DESCRIPTION

"Method and system for clamping force estimation"

Technical field

This application relates to a method and system for clamping force estimation.

Background art

Numerous technological applications rely on joints based on fasteners for components of dissimilar plate materials. A secured connection throughout the lifetime of a joint is a key factor in many systems, since vibration and external loads may cause the joint self-loosen or unscrew and result in failure of a given structure. Therefore, estimation of the force required in each joint is necessary for a guaranteed connection throughout the life of any given assembly. However, the direct measurement of forces in most systems is a difficult task due to large forces and the problems associated with installation of force transducers.

Thus, indirect methods are used to estimate input forces based on dynamic response of systems. There are few methods in the literature based on vibration analysis that claim to estimate force in beam and cable systems. However, there is no report to force estimation in joints. Consider a plate cover joined securely by a variable number of fasteners elements, such as screws, rivets or clips, as a practical example. The cover system thus forms a closed protection system for many industrial applications, whose rigidity is dependent on the connecting joints. But since there is no criterion or way of determining the integrity of the system based on the number of joining elements, the designer usually increases the number of joints by common sense and personal experience. The excessive number of elements does not contribute to the stiffness of the final product and, in return, will increase the complexity and final cost of the product, especially high-volume manufacture.

There are a few number of studies on force estimation of beams and cables using vibration in the literature. The patent application EP 2283567 B1 disclose a method and device for estimating the clamping force required for winding a package of a transformer based on the vibration generated by passing a pulse through the winding. However, there is no report of vibration-based force estimation in joints.

In this regard, the document EP 2184136 A1 describes a method and equipment for estimation of tightening force for fastening members during the assembling and exploiting period, by comparing one or several of its measured dynamic characteristics – such as amplitude frequency, amplitude phase or frequency-phase characteristics - with the correspondent theoretical values. The dynamic characteristics are taken from natural vibrations excited by light impact to bolt or nut, by recording these vibrations as relative and, in other case, as absolute vibrations by sensor for further computer analysis.

The document US 5974919 A1 describes a screwing device for ultrasound-controlled tightening of screw connections. Said screwing device comprises a vibration body, for example, a piezoelectric crystal which, with corresponding electric excitation, produces high-frequency acoustic vibrations and conducts the same into the screw connection. By comparing excitation signals and echo signals is a schematically represented evaluation device, conclusions are made as to the voltage state in the screw connection and, consequently, as to the current screwing torque.

Summary

The present application describes a method for estimating the clamping force associated to a fastener element in a joint system, characterized by comprising the following steps:

- Application of a vibration to a joint plate sample;
- Measurement of the first resonant frequency of a joint of the sample;
- Application of a vibration to the sample at the first resonance frequency of said joint in sinusoidal mode, calculated in previous step;
- Measurement of force and acceleration values in said joint, resulting from the vibration applied to sample in previous step;
- Application to the sample of at least two different amplitude levels of vibration at the first resonant frequency of the joint, calculated in previous steps;
- Measurement of the respective force and acceleration values;
- Calculation of the mass of the joint, based on the set of force and acceleration values measured in previous steps.

In one embodiment of the method, the vibration applied to the joint plate sample is in the range of 0 to 200 Hz.

In another embodiment of the method, the first resonance frequency of the joint is determined by calculating the frequency response function of the acceleration over a time period.

Yet in another embodiment of the method, the time period is 10 seconds.

In another embodiment of the method, the joint's response data to applied vibrations are collected as functions of force vs. time and acceleration vs. time over a time period.

Yet in another embodiment of the method, said time period is 2 seconds.

Finally, in another embodiment of the method, the force and acceleration values are calculated as the sum of average maximum and minimum amplitudes divided by 2.

The present application also describes a system for estimating the clamping force associated to a fastener element in a joint system, configured to implement the developed method comprising:

- A frequency generator, configured to generate random frequency vibration profiles to excite the joint plate sample;
- An amplifier connected to the frequency generator, adapted to provide different amplitude levels of vibration;
- A sensor unit, comprised by a force sensor and an accelerometer;

- A spectrum analyzer configured to measure the sinusoidal functions provided by the force sensor and the accelerometer;
- A computing unit, configured to calculate the frequency response function and to determine the joint's first resonance frequency, from the data provided by the spectrum analyzer, and to calculate the mass of the joint, based on the set of force and acceleration values measured.

In one embodiment of the system, the frequency generator is a shaker.

General Description

The present application relates to a method and system for estimating a clamping force associated to each fastener element in a joint system, based on the vibration generated by dynamic loads. In the context of this description, a joint system is assumed a mechanical assembly formed by at least two plate materials joint by a variable number of fastener elements including bolts, screws, clicks, rivets or snaps.

The method developed intends to solve the problem of determining the critical force applied to each fastener element, required to maintain a healthy and durable joint, minimizing the risk of unscrewing or self-loosening in joint plate materials. In connection to this, the method also allows determining the most effective position for the fastener elements in the joint. In fact, it is an object of the method developed to provide accuracy for measuring the clamping force in connection joints by means of which a designer may identify excessive connecting elements, making the joint system more efficient, economical and environmentally friendly. This method can be applied in joint systems made of various plate materials with different number of connections.

In keeping with these objects and with others which will become apparent hereinafter, one feature of the method developed resides, briefly stated, on a method for estimating a clamping force required by each fastener element in a joint system, based on the vibration generated by dynamic loads, in which the number of connection points and respective clamping forces in the joint system take in consideration the forces applied in each joint due to system acceleration.

The method is based on application of vibration to a joint plate sample, at free-free boundary conditions, and is implemented in two stages: in the first stage, the first resonance frequency of the joint is measured. In the second stage, the joint is subjected to vibration at the first resonance frequency, obtained from stage one, in sinusoidal mode, to estimate the force and acceleration of each joint. This method is based on vibration analysis to determine the local mass, and consequently the local dynamic force applied to a fastener element when subject to external loads, taking in consideration the mass distribution, rigidity and elastic features of the materials forming the joint system.

Another object of the present application is to provide a system for estimating a clamping force required by each fastener element in a joint system. Such system comprises a frequency generator, configured to generate random frequency vibration profiles, sufficient to excite the joint system; an amplifier module connected to the frequency generator to provide different amplitude levels of vibration; a sensor unit, comprised by an accelerometer and a force sensor, for measuring the respective quantities resulting from the vibrations generated by the frequency generator in said joint; a spectrum analyzer configured to measure the sinusoidal functions provided by the force sensor and the accelerometer; and a computing unit configured to calculate the frequency response function and to determine the joint's first resonance frequency of stage one, from the data provided by the spectrum analyzer, and to calculate the mass of each joint, based on the set of force and acceleration values collected.

Brief description of drawings

For easier understanding of this application, figures are attached in the annex that represent the preferred forms of implementation which nevertheless are not intended to limit the technique disclosed herein.

Figure 1 illustrates the conceptual block diagram of the system for estimating a clamping force required by each fastener element in a joint system, in which the reference numbers represent:

1 – Spectrum analyzer;
2 – Amplifier;
3 – Computing unit;
4 – Joint plate sample;
5 – Frequency generator;
6 – Accelerometer;
7 – Force sensor.

Figure 2 illustrates an example of a joint plate sample comprised of four joints with respective fastener elements, in which the reference numbers represent:

4 – Joint plate sample;
8 – Joint.

Figure 3 shows the estimation of an expected mechanical resonant frequency response graph, obtained for a given joint.

Figure 4 shows the estimation of the maximum force response as a function of time, for a given joint subject to its first resonant frequency.

Figure 5 shows the estimation of the maximum acceleration response as a function of time, for a given joint subject to its first resonant frequency.

Figure 6 shows the estimation of the force (p) – acceleration ($\ddot{x}$) linear regression graph for the joint plate sample of figure 2, wherein the dashed line represents the experimental procedure presented, while the solid one is the linear regression that best fits the experimental curve.

Description of the embodiments

Now, embodiments of the present application will be described in detail with reference to the annexed drawings. However, they are not intended to limit the scope of this application.

The method now developed is based on vibration analysis to determine the local mass, and consequently the local dynamic force applied to a fastener element when subject to external loads. For a dynamic system with multiple degrees of freedom (MDF), the equation of motion that represents the dynamic response when subject to external vibration, is expressed in the general matrix form (Eq.1):

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = p(t) \qquad \text{(Eq.1)}$$

Where **M**, **C** and **K** denote mass, damping and stiffness matrices of the system, respectively, and $\ddot{x}(t)$, $\dot{x}(t)$ e $x(t)$ are the acceleration, velocity, displacement and external excitation time-dependent vectors, respectively. For an undamped and unexcited system, Eq.1 may be rewritten as:

$$M\ddot{x}(t) + Kx(t) = 0 \qquad \text{(Eq.2)}$$

The solution of the second order homogeneous linear system in Eq.2 can be written as:

$$x(t) = \varphi_i \cos(\omega_i t + \psi_i) \qquad \text{(Eq.3)}$$

Where ψ_i is the phase shift angle, φ_i an eigenvector and ω_i the natural circular frequency (rad/s). The second order derivative of Eq.3 with respect to t, would be:

$$\ddot{x}(t) = -\omega_i^2 \varphi_i \cos(\omega_i t + \psi_i), \qquad \text{(Eq.4)}$$

And by substitution of Eq.3 and Eq.4 in Eq. 2, one will have:

$$\mathbf{K}\cdot \varphi_i = \omega_i^2 \cdot \mathbf{M}\cdot \varphi_i \qquad \text{(Eq.5)}$$

The multiplication of Eq.5 by $\mathbf{M}^{-1}$ will result in:

$$\mathbf{M}^{-1} \cdot \mathbf{K} \cdot \varphi_i = \omega_i^2 \varphi_i \qquad \text{(Eq.6)}$$

By substituting the identity matrix, **I**, one will have

$$(\mathbf{M}^{-1} \cdot \mathbf{K} - \omega_i^2 \cdot \mathbf{I})\varphi_i = 0 \qquad \text{(Eq.7)}$$

In order for a non-trivial solution to exist, the term $\mathbf{M}^{-1}\cdot\mathbf{K} - \omega_i^2\cdot\mathbf{I}$ must be singular and therefore:

$$\det(\mathbf{M}^{-1}\cdot\mathbf{K} - \omega_i^2\cdot\mathbf{I}) = 0 \qquad \text{(Eq.8)}$$

thus, from $\det(\mathbf{M}^{-1}\cdot\mathbf{K} - \lambda_i\cdot\mathbf{I}) = 0$ the eigenvalues $\lambda_i = \omega_i^2$ can be determined. If the dynamic system is subject to vibration at a resonance frequency f_i in sinusoidal mode, where $f_i = \sqrt{\omega_i/2\pi}$, the periodic input force $p(t)$ is defined as:

$$p(t) = P\cos(\omega_i t + \psi_i) \qquad \text{(Eq.9)}$$

In which P denotes the force amplitude. Using Newton's second law for a single DOF system of both rigid and flexible bodies, the Eq.1 may be rewritten as:

$$m\cdot\ddot{x}(t) = p(t) \qquad \text{(Eq.10)}$$

Substituting Eq.4 in Eq.10, one can obtain:

$$P = m\cdot\left\|-\omega_i^2\varphi_i\right\| \qquad \text{(Eq.11)}$$

Where $\left\|-\omega_i^2\varphi_i\right\|$ is the amplitude of acceleration, m is the slop (or the mass that can be supported by the joint) and P is the force in a given joint.

The method developed is based on the application of vibration to joint plate samples (4) at free-free boundary conditions, and is implemented in two stages. In a first stage, the first resonance frequency of a joint (8) of the plate sample (4) is measured. In the second stage, said joint (8) is subjected to vibration at the first resonance frequency, obtained from the first stage, in sinusoidal mode, to estimate the force and the acceleration parameters of the joint (8).

In the first stage, vibration is applied to the plate sample (4) by means of a frequency generator (5). In an embodiment, the frequency generator (5) is a shaker that supplies random frequencies from 0 to 200Hz. The force sensor (7) and the accelerometer (6) are coupled and provide sinusoidal functions, by which the maximum force and acceleration associated with each joint (8) in the sample (4) may be obtained by the circuit illustrated by diagram blocks in Figure 1. The amplifier (2) is connected to the shaker to provide different amplitude levels of vibration to the sample (4), and the response data is recorded as the acceleration over a time period, and then converted to a Frequency Response Function. In an embodiment, the response data is recorded as the acceleration over time for a time period of 10 seconds.

In the second stage, the joint plate sample (4) is subject to vibration at the first resonance frequency in sinusoidal mode of the joint (8). The response data is collected by the spectrum analyzer (1) as functions of force vs. time and acceleration vs. time throughout a time period. In an embodiment said time period is of 2 seconds. Figures 4 and 5 show an estimation of the sinusoidal functions of force and acceleration versus time for a joint (8) of the sample (4) shown in Figure 2.

The force and acceleration values are calculated as the sum of average maximum and minimum amplitudes, divided by 2. This approach is also repeated for at least two different amplitude levels of vibration - at the first resonant frequency -, adjusted by the amplifier (2), which allows obtaining several values of force and acceleration, in order to obtain a linear relation between both quantities. In an embodiment, the force and acceleration values are calculated for three different excitation amplitudes, which allows obtaining three values of force and acceleration yielding the graph shown in Figure 6. The same procedure is repeated for each joint (8) of the sample (4).

This description is of course not in any way restricted to the forms of implementation presented herein and any person with an average knowledge of the area can provide many possibilities for modification thereof without departing from the general idea as defined by the claims. The embodiments described above can obviously be combined with each other. The following claims further define the forms of implementation.

CLAIMS

1. Method for estimating the clamping force associated to a fastener element in a joint system, comprising the following steps:
   - Application of a vibration to a joint plate sample;
   - Measurement of the first resonant frequency of a joint of the sample;
   - Application of a vibration to the sample at the first resonance frequency of said joint in sinusoidal mode, calculated in previous step;
   - Measurement of force and acceleration values in said joint, resulting from the vibration applied to sample in previous step;
   - Application to the sample of at least two different amplitude levels of vibration at the first resonant frequency of the joint, calculated in previous steps;
   - Measurement of the respective force and acceleration values;
   - Calculation of the mass of the joint, based on the set of force and acceleration values measured in previous steps.

2. Method according to claim 1, wherein the vibration applied to the joint plate sample is in the range of 0 to 200 Hz.

3. Method according to any of the previous claims, wherein the first resonance frequency of the joint is determined by calculating the frequency response function of the acceleration over a time period.

4. Method according to claim 3, wherein the time period is 10 seconds.

5. Method according to any of the previous claims, wherein the joint’s response data to applied vibrations are collected as functions of force vs. time and acceleration vs. time over a time period.

6. Method according to claim 5, wherein said time period is 2 seconds.

7. Method according to claim 5 or 6, wherein the force and acceleration values are calculated as the sum of average maximum and minimum amplitudes divided by 2.

8. System for estimating the clamping force associated to a fastener element in a joint system, configured to implement the method of claims 1 to 7, comprising:

- A frequency generator, configured to generate random frequency vibration profiles to excite the joint plate sample;
- An amplifier connected to the frequency generator, adapted to provide different amplitude levels of excitation;
- A sensor unit, comprised by a force sensor and an accelerometer;
- A spectrum analyzer configured to measure the sinusoidal functions provided by the force sensor and the accelerometer;
- A computing unit, configured to calculate the frequency response function and to determine the joint’s first resonance frequency, from the data provided by the

spectrum analyzer, and to calculate the mass of the joint, based on the set of force and acceleration values collected.

9. System according to claim 8, wherein the frequency generator is a shaker.

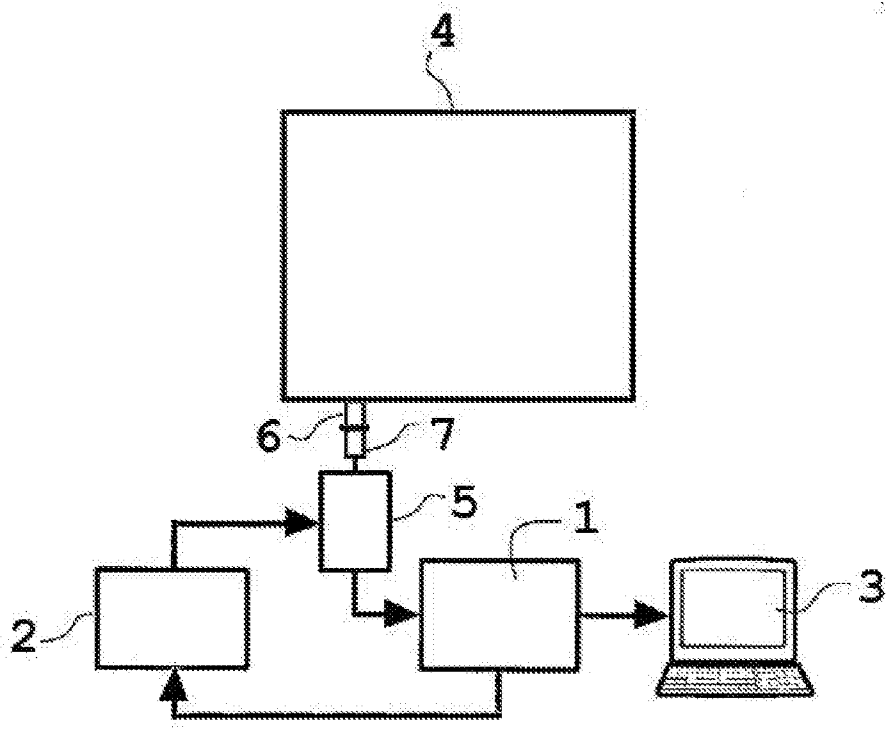

Figure 1

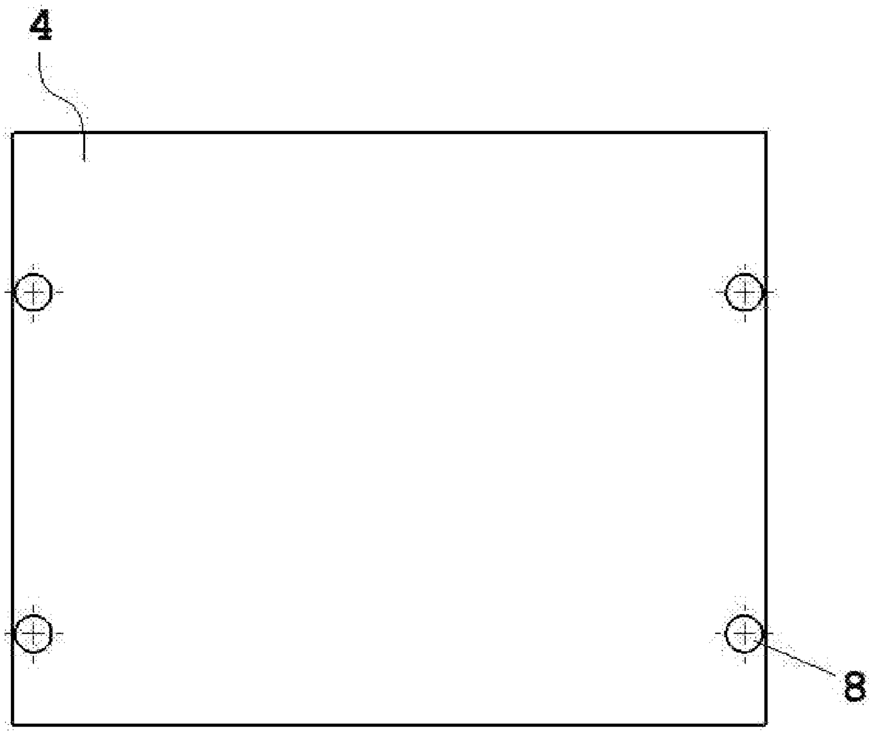

Figure 2

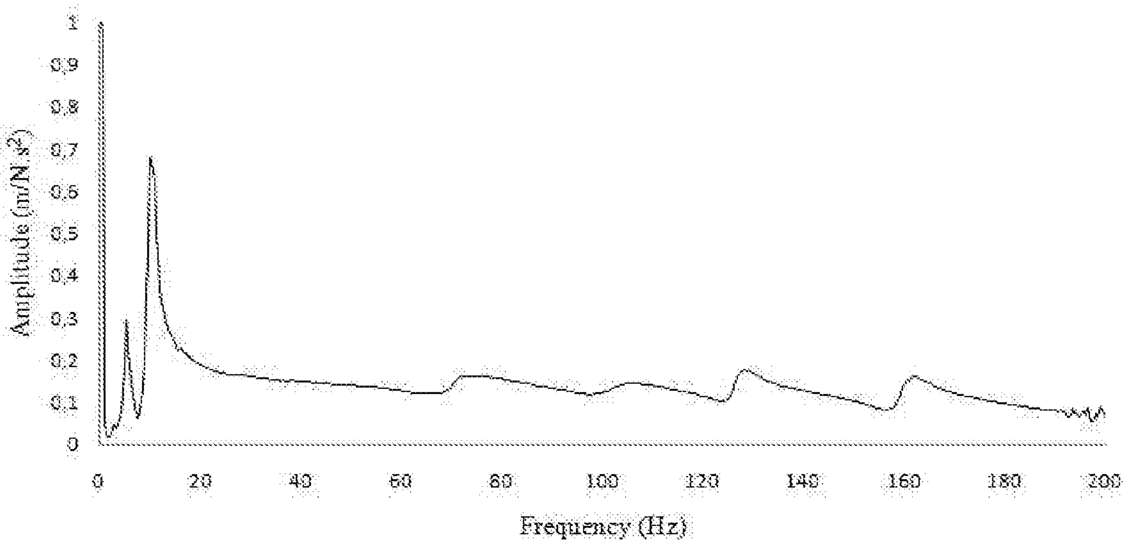

Figure 3

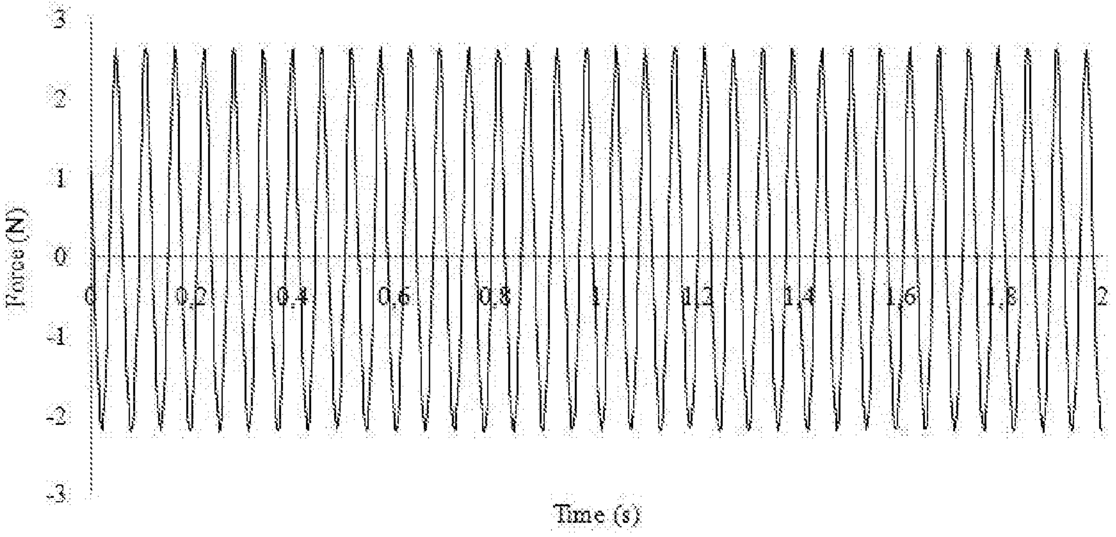

Figure 4

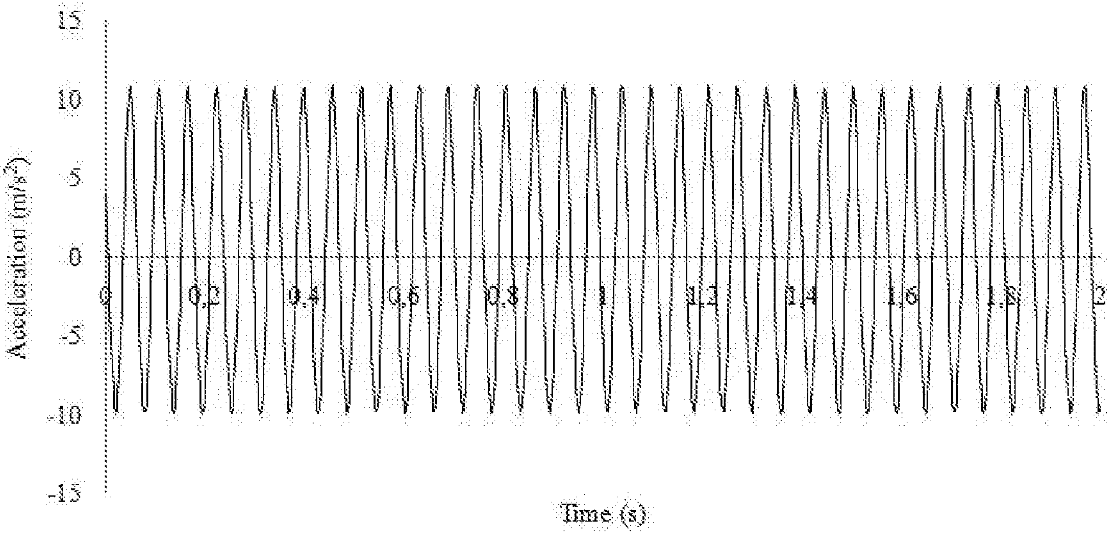

Figure 5

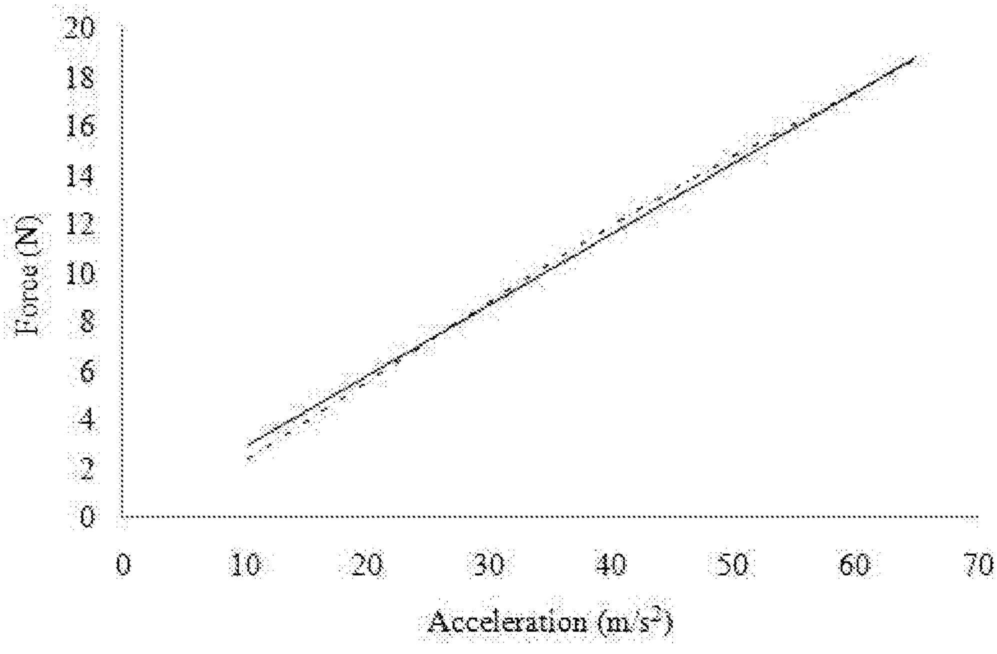

Figure 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/055012

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01L5/24
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01L G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 02/095346 A1 (SENSOR SYSTEM CO LTD [JP]; YANO HIROAKI [JP]; TANAKA MINORU [JP]) 28 November 2002 (2002-11-28) abstract paragraphs [0040] - [0042], [0044], [0045] -----	1-9
A	US 5 060 516 A (LAU PETER W [CA] ET AL) 29 October 1991 (1991-10-29) abstract column 5, lines 16-45 -----	1,8
A	EP 2 523 005 A1 (BAE SYSTEMS PLC [GB]) 14 November 2012 (2012-11-14) abstract figure 1 -----	9

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search
19 March 2019

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2018/055012

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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