United States Patent	12395100
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Saari; Byron John et al.

Combination piezoelectric actuator and sensor

Abstract

A test system includes a frame. A hydraulic actuator is mounted to the frame and is configured to support a test specimen. A piezoelectric actuator is configured to apply a force to the test specimen. A controller is configured to excite the piezoelectric actuator and provide an indication of force generated by the piezoelectric actuator by measurement of current or charge provided to the piezoelectric actuator.

Inventors:	**Saari; Byron John (Minneapolis, MN), Johnson; Scott Gale (Waconia, MN)**
Applicant:	**MTS Systems Corporation** (Eden Prairie, MN)
Family ID:	**1000008762877**
Assignee:	**MTS SYSTEMS CORPORATION (Eden Prairie, MN)**
Appl. No.:	**17/438817**
Filed (or PCT Filed):	**November 04, 2019**
PCT No.:	**PCT/US2019/059688**
PCT Pub. No.:	**WO2020/093054**
PCT Pub. Date:	May 07, 2020

Prior Publication Data

Document Identifier	**Publication Date**
US 20220131479 A1	Apr. 28, 2022

Related U.S. Application Data

us-provisional-application US 62755508 20181104

Publication Classification

Int. Cl.: **G01N3/36** (20060101); **G01N3/38** (20060101); **H02N2/04** (20060101); **H02N2/18** (20060101)

U.S. Cl.:

CPC **H02N2/04** (20130101); **G01N3/36** (20130101); **G01N3/38** (20130101); **H02N2/183** (20130101); G01N2203/0048 (20130101); G01N2203/0051 (20130101); G01N2203/0623 (20130101)

Field of Classification Search

CPC: G01N (3/32); G01N (3/36); G01N (3/38); G01N (2203/0048); G01N (2203/0051); G01N (2203/0623); H02N (2/04); H02N (2/183)

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5856620	12/1998	Okada	N/A	N/A
6209382	12/2000	Komata et al.	N/A	N/A
6561019	12/2002	Kossat et al.	N/A	N/A
6813960	12/2003	Owen et al.	N/A	N/A
7331209	12/2007	Saari et al.	N/A	N/A
8252416	12/2011	Jun et al.	N/A	N/A
9658122	12/2016	Saari et al.	N/A	N/A
2006/0056832	12/2005	Yamaguchi et al.	N/A	N/A
2006/0070424	12/2005	Saari et al.	N/A	N/A
2010/0066423	12/2009	Inukai et al.	N/A	N/A
2016/0202160	12/2015	Saari	73/788	G01N 3/02
2016/0245733	12/2015	Cerutti	N/A	G01N 3/38

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
2090527	12/1990	CN	N/A
101868260	12/2009	CN	N/A
10022759	12/2000	DE	B60T 13/74
S5918429	12/1983	JP	N/A
H08285753	12/1995	JP	N/A
2000-510595	12/1999	JP	N/A
3429322	12/2002	JP	N/A
2008-164495	12/2007	JP	N/A
2008-285753	12/2007	JP	N/A
2009-258900	12/2008	JP	N/A
2009-280974	12/2008	JP	N/A
2010-014404	12/2009	JP	N/A

2013-019768	12/2012	JP	N/A
199837400	12/1997	WO	N/A
2009101566	12/2008	WO	N/A

OTHER PUBLICATIONS

International Search Report and Written Opinion for corresponding International Application No. PCT/US2019/059688 dated Feb. 19, 2020. cited by applicant
Furutani et al. “Estimation of Generative Force of Piezoelectric Actuator by Using Driving Current”, Journal of the Japan Society for Precision Engineering, 2015, pp. 875-880, vol. 81, No. 9. cited by applicant
Office Action in corresponding European patent application No. 19809340.3 dated Sep. 6, 2023. cited by applicant
Office Action in corresponding Japanese patent application No. 2021-523905 dated Oct. 19, 2023. cited by applicant
Office Action in corresponding Chinese patent application No. 201980073048.6 dated Apr. 18, 2024. cited by applicant
Final Office Action in corresponding Japanese patent application No. 2021-523905 dated May 10, 2024. cited by applicant
Office Action in corresponding Chinese patent application No. 201980073048.6 dated Sep. 28, 2024. cited by applicant
Office Action in corresponding Korean patent application No. 10-2021-7016649 dated Nov. 20, 2024. cited by applicant

---

Primary Examiner: Huls; Natalie

Attorney, Agent or Firm: Westman, Champlin & Koehler, P.A.

Background/Summary

(1) The present application is a Section 371 National Stage Application of International Application No. PCT/US2019/059688, filed Nov. 4, 2019 and published as WO 2020/093054 A1 on May 7, 2020, in English, and further claims priority to U.S. provisional patent app. Ser. No. 62/755,508, filed Nov. 4, 2018.
BACKGROUND
(2) The discussion below is merely provided for general background information and is not intended to be used as an aid in determining the scope of the claimed subject matter.
(3) For testing of components or materials, such as elastomer materials or parts, it is often desirable to measure the force response of the material to a motion input excitation. The measured force divided by the excitation displacement is referred to as the dynamic stiffness. The phase relationship between the force and displacement is also an important characteristic for the material and component properties. This dynamic stiffness measurement or characterization is often performed with very high frequency excitations. An example is for characterizing the dynamic stiffness and transmissibility for automotive motor mounts. Common excitation frequencies for internal combustion engine motor mount testing is from 0.01 Hz to 1,000 Hz. This type of testing is often performed with servo-hydraulic test equipment. Higher frequency dynamic stiffness measurements up to 2.000 Hz or even 3.000 Hz frequency is becoming more desirable with a more concentrated focus on noise, vibration and harshness (NVH) in the automotive manufacturing industry due to consumers higher NVH expectation combined with the influence of the quieter

electric vehicles. Servo-hydraulic actuation technology becomes less efficient and more complicated at frequencies above 1,000 Hz. The compliance of the hydraulic oil makes it difficult to realize sizable motions above 1000 Hz.

SUMMARY

(4) This Summary and the Abstract herein are provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary and the Abstract are not intended to identify key features or essential features of the claimed subject matter, nor are they intended to be used as an aid in determining the scope of the claimed subject matter. The claimed subject matter is not limited to implementations that solve any or all disadvantages noted in the Background.

(5) This disclosure proposes an alternative piezoelectric (PE) actuation technology particularly advantageous for higher (>1,000 Hz) excitation frequencies. Piezoelectric (PE) actuators have been used for higher frequency dynamic stiffness measurement/characterization testing. One disadvantage of the PE technology is that it typically is not feasible for low frequency testing such as less than 80 Hz. This is probably due to the limited stroke/displacement achievable from a PE actuator. One aspect of the invention is using PE actuators in combination with hydraulic actuation technology to achieve a testing system which can test at frequencies greater than about 1,000 Hz, in one embodiment for testing at frequencies in a bandwidth of about 0.01 Hz to greater than about 1,000 Hz, in another embodiment for testing at frequencies in a bandwidth of about 0.01 Hz to about 2,000 Hz, and in yet another embodiment for testing at frequencies in a bandwidth of about 0.01 Hz to about 3,000 Hz.

(6) Another aspect is the dual use of the PE actuator/sensor. As mentioned above, the characteristic mostly studied during this form of testing is the dynamic stiffness. This stiffness is derived from a measurement or estimation (in the truest sense, a transducer measurement is only an “estimation” of a physical quantity) of the displacement and the force. The displacement estimate is often derived from an LVDT or an encoder at low frequencies, and is often derived from an acceleration based measurement at higher frequencies, where the acceleration is estimated from an accelerometer measurement. The acceleration is double integrated to derive the displacement. The force is often estimated from a strain gaged force transducer measurement. Another force transducer sometimes used for this type of testing is a piezoelectric force transducer. In a PE force transducer, the rate of change of force is proportional to the electrical charge emitted from the PE element. Also note that the strain (which is proportional to displacement) of the PE actuator is proportional to the voltage applied to the PE actuator element.

(7) Another aspect of the invention is to accurately measure the current/charge within the PE actuator motor amplifier which is delivered to the PE actuator during the test excitation. Then from this current/charge measurement, estimate the force produced by the PE actuator. The advantage of this combination PE actuator/sensor is that the component costs can be reduced since the PE transducer can be eliminated since the PE actuator (along with the current/charge measurement) can perform this function.

(8) In one embodiment, a test system includes a frame and a hydraulic actuator mounted to the frame and configured to support a test specimen. A piezoelectric actuator is configured to apply a force to the test specimen; and a controller is configured to excite the piezoelectric actuator and provide an indication of force generated by piezoelectric actuator by measurement of current or charge provided to the piezoelectric actuator.

(9) In another embodiment, a test system includes a frame and a hydraulic actuator mounted to the frame and configured to support a test specimen, the hydraulic actuator having a movable element such as a piston rod. An inertial mass is coupled to the movable element to move therewith. A piezoelectric actuator is mounted to the inertial mass on a side opposite the movable element. The piezoelectric actuator is configured to apply a force to the test specimen. The test system also includes a controller configured to control operation of the hydraulic actuator and excite the

piezoelectric actuator.

(10) Implementations of the foregoing may include one or more of the following features. The test system where the piezoelectric actuator is connected in series with the hydraulic actuator. A load cell can be provided and configured to connect to the test specimen on a side opposite of the hydraulic actuator. In another embodiment, a mass is configured to connect to the test specimen on a side opposite of the hydraulic actuator and a load cell connected to the second mass. The foregoing structure allows the controller to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies greater than about 1,000 hz, and in a further embodiment at frequencies in a bandwidth of about 0.01 hz to greater than about 1,000 hz, and in a further embodiment at frequencies in a bandwidth of about 0.01 hz to greater than about 2,000 hz, and in yet a further embodiment at frequencies in a bandwidth of about 0.01 hz to greater than about 3,000 hz.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a schematic representation of an exemplary testing machine.

(2) FIG. **2** is a schematic representation of a controller of the testing machine of FIG. **1**.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENT

(3) Referring to the figures, an exemplary embodiment of a combination PE and hydraulic actuator system **10** is integrated into a typical servo-hydraulic testing system **11** such as the MTS **831**.**50**, manufactured by MTS Systems Corporation of Eden Prairie, Minn. The test system **11** includes a frame **10** having herein a base **13** and two columns **15** that support a crosshead **17**. Generally, the system **11** includes a hydraulic actuator **12** (herein mounted in the crosshead **17** by way of example) and a PE actuator **14**. In this exemplary embodiment, an inertial mass **16** is attached to a piston rod **18** of the hydraulic actuator **12** to provide an inertial reaction for the PE actuator **14**. The PE actuator **14** can be disposed in series between inertial mass **16** above a specimen under test (SUT) **22** and/or the PE actuator can be secured to the SUT **22** as shown in the FIG. **1** at **14′** on a side opposite the inertial mass **16** with an accelerometer **24′** in series with the PE actuator **14′** and the SUT **22**. For the high frequency testing, the accelerometer(s) **14**, **14′** can be used for a displacement estimation. Accelerometers **24**, **24′** can be used to derive a relative acceleration hence relative displacement across the SUT **22** as described in United States Published Patent Application 2016/0202160, which is incorporated herein by reference in its entirety.

(4) Since a PE transducer cannot measure to very low frequencies, another transducer such as a strain gage load cell **30** is provided. If desired, an accelerometer **26** can also be mounted to the load cell **30** and used for force transducer acceleration compensation as described in U.S. Pat. Nos. 7,331,209 or 9,658,122, which are incorporated herein by reference in their entirety.

(5) The load cell transducer **30** can be located under the optional PE actuator/transducer **14′** which is under the SUT **22**. In another embodiment, it may be desirable to include another inertial mass directly under the lower optional PE actuator/transducer **14′** in which case the load cell can be located **30′** and the inertial mass is then represented by reference **30**. Or alternatively a delta P transducer can be used to measure fluid pressure on opposite side of the piston of the actuator **12** and the load cell can be removed entirely. It should be noted in yet another embodiment, multiple PE actuator/transducers can be used. For instance, both PE actuator/transducer **24** and **24′** can be used as illustrated. Likewise, multiple PE actuator/transducers can be used in series where indicated at **14** or **14′**.

(6) A controller **34** controls operation of the hydraulic actuator **12** and PE actuator/transducer **14**. As is well known in the art, the controller **34** typically controls operation of the hydraulic actuator **12** by providing control signals to a servovalve **36** that in turn controls fluid flow to the hydraulic

actuator **12**. The controller **34** directly or indirectly through an interface module (actuator amplifier) excites the PE actuator(s) in the system **11**. The current/charge delivered by the PE actuator motor amplifier to the PE actuator during test excitation is measured. In one embodiment, the current to each of the PE actuator/transducers **14**, **14′** is measured by a current sensor, the signal of which is integrated over time so as to provide a total charge measurement. To avoid drift the current signal is provided to a high pass filter and then integrated. Then from this total charge measurement, the controller **34** estimate the force produced by the PE actuator from a believed linear relationship, although any nonlinearities can also be taken into account if present. The strain, which is proportional to displacement, can be ascertained by measuring the voltage applied to the PE actuators **14**, **14′**.
(7) Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

Claims

1. A test system comprising: a frame; a hydraulic actuator mounted to the frame configured to provide a force to a test specimen; a piezoelectric actuator configured to apply a second force to the test specimen; and a controller configured to excite the piezoelectric actuator and provide an indication of the second force generated by the piezoelectric actuator by measurement of current or charge provided to the piezoelectric actuator.
2. The test system of claim 1 wherein the piezoelectric actuator is connected in series with the hydraulic actuator.
3. The test system of claim 1 and a load cell configured to measure force applied to the test specimen.
4. The test system of claim 1 and a mass connected to a piston rod of the hydraulic actuator.
5. The test system of claim 4 and a load cell supported on the frame on a side opposite of the hydraulic actuator, the load cell configured to measure and provide an input signal to the controller indicative of the force applied to the test specimen.
6. The test specimen of claim 5 and a second mass configured to connect to the test specimen on a side opposite of the hydraulic actuator and a second load cell connected to the second mass.
7. The test system of claim 1 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies greater than or equal to 1,000 Hz.
8. The test system of claim 1 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies in a bandwidth of 0.01 Hz to greater than 1,000 Hz.
9. The test system of claim 1 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies in a bandwidth of 0.01 Hz to greater than 2,000 Hz.
10. The test system of claim 1 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies in a bandwidth of 0.01 Hz to greater than 3,000 Hz.
11. The test system of claim 1 wherein the frame comprises a base and two support columns supporting a crosshead over the base.
12. The test system of claim 11 wherein the hydraulic actuator is located in the crosshead.
13. The test system of claim 1 and further comprising an inertial mass coupled to a piston rod of the hydraulic actuator to move therewith, and wherein the piezoelectric actuator is mounted to the inertial mass, and wherein the piezoelectric actuator supports the test specimen on a side opposite the inertial mass.
14. A test system comprising: a frame; a hydraulic actuator mounted to the frame configured to

provide a force to a test specimen, the hydraulic actuator having a piston and being mounted in a crosshead; an inertial mass coupled to the piston to move therewith; a piezoelectric actuator mounted to the inertial mass on a side opposite the piston, the piezoelectric actuator configured to apply a second force to the test specimen; and a controller configured to control operation of the hydraulic actuator, excite the piezoelectric actuator and provide an indication of the second force generated by the piezoelectric actuator by measurement of current or charge provided to the piezoelectric actuator.

15. The test system of claim 14 and further comprising a load cell supported on the frame on a side opposite of the hydraulic actuator, the load cell configured to measure and provide an input signal to the controller indicative of a force applied to the test specimen.

16. The test system of claim 15 and further comprising a second inertial mass connected to the load cell on a side opposite the frame.

17. The test system of claim 16 and further comprising a piezoelectric transducer connected to the second inertial mass on a side opposite the load cell, the piezoelectric transducer configured to measure and provide a second input signal to the controller indicative of the force applied to the test specimen.

18. The test system of claim 14 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies greater than or equal to 1,000 Hz.

19. The test system of claim 14 wherein the controller is configured to operate the hydraulic actuator and piezoelectric actuator for test specimen testing at frequencies in a bandwidth of 0.01 Hz to greater than 2,000 Hz.