NASA TECHNICAL MEMORANDUM NASA TM-75444

USE OF PIEZOELECTRIC MULTICOMPONENT FORCE MEASURING DEVICES IN FLUID MECHANICS

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Translation of "Anwendung piezoelektrischer Mehrkomponenten-Kraftmesser in der Strömungsmechanik," Archiv für technisches Messen/ Messtechnische Praxis, No. 446, March, 1973, pp. 41-44

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 SEPTEMBER 1979

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A. Richter and K. Stefan

1. Introduction /41*

Several techniques are currently available for the electrical measurement of force. The systems most often used are force-measuring devices with resistance strain gauges. Inductive and capacitive transducers are also used with increasing frequency. These systems are called passive transducers, i.e., they require electric energy. An active transducer which has attained widespread use is the piezoelectric quartz transducer.

Although the advantages of piezoelectric measuring devices are generally known in terms of their good resolution of rapidly- and strongly-fluctuating loads, they are utilized in relatively few areas. This is less true of the single-component force- or pressure-measuring elements than of multicomponent force-measuring devices. For the most part, the multicomponent devices have found application only in the areas for which they were specifically developed.

The reason for the infrequent use of piezoelectric devices for measuring multidirectional forces in other technical fields apparently stems from a lack of either stimulus or demand.

More than ever before, it should be possible to utilize piezoelectric measuring elements for the measurement of oscillations and the fluctuating forces that accompany them. It is hoped that the example presented here, involving the use of multicomponent

* Numbers in the margin indicate pagination in the foreign text.

devices for the measurement of fluctuating forces associated with flow, will serve as an impetus for the further development of piezoelectric measuring technology.

2. Properties of Piezoelectric Multicomponent Transducers

The property of certain crystal surfaces to give off electric charge when subjected to an external mechanical stress is called the direct piezoelectric effect. This effect was first demonstrated by Curie in 1880. The process is reversible. A distinction is made between the longitudinal piezoelectric effect, transverse piezoelectric effect and the shear effect, depending on the direction in which the force is applied. Further details on piezoelectric properties can be found in the specialized literature, e.g., [1, 2].

Quartz is used because it has significant advantages over other piezoelectric materials tested (tourmaline, rochelle salt, barium titanate):

-- high mechanical load capacity, resulting in a highly rigid pickup and large measurement range;

-- high specific resistance, advantageous for quasi-static measurements;

-- low temperature dependence ($T_k \simeq 2 \cdot 10^{-4}/°C$);

-- high natural frequency (several kHz, depending on the mass of the pickup);

-- linear characteristic ($\leq \pm 1\%$ deviation).

Several plates cut from the quartz at right angles to the various crystal axes can be stacked to form a single, compact measuring element which is capable of resolving an applied force into its directional components [3]. If a force is applied from an arbitrary direction, a change of charge is produced in each of the plates which is proportional to the force component in the "sensitive" direction (Fig. 1). A charge-measuring amplifier is used to transform the change of charge into a voltage which is proportional to it. This device consists of an integrating amplifier with a very high insulation resistance. The charge changes which are proportional to the integral of the force changes are integrated in the amplifier onto a capacitor, which delivers a proportional output voltage at the amplifier output [4, 5]. Since the relatively high gain of the charge-measuring amplifier is almost completely coupled back in phase opposition, the device might best be described as a "charge-voltage transformer."

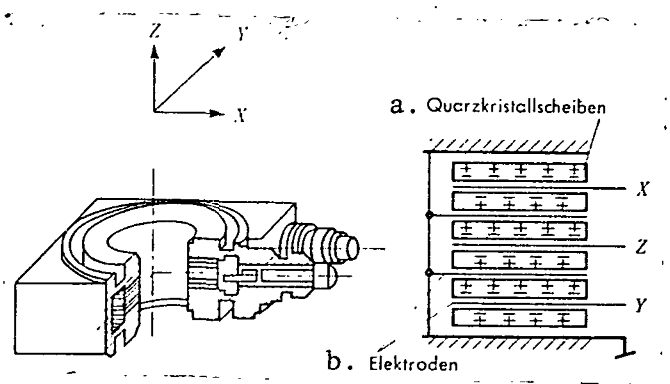

Fig. 1. Diagrammatic sketch of a 3-component piezoelectric transducer.

Key: a - Quartz crystal plates; b - Electrodes.

Of course even multicomponent piezoelectric force-measuring devices have advantages and disadvantages in comparison with other measuring systems. One advantage in particular is the extreme rigidity of the piezoelectric transducer, since only extremely short excursions are needed to produce a change of charge. Its very high natural frequency (dependent on the mass of the measuring system) allows large ranges of measurement. The high linearity of ±1% corresponds to the precision of the crystal cuts and may be diminished in practice by inaccuracies in the transmission of forces to the crystals. A particularly favorable property of the quartz transducer is its low T_k value of 0.02% per °C. One disadvantage is that static and long-term measurements are not possible in principle, since even /42 an extremely high input resistance of about 10^{14} Ω represents a finite value, resulting in the gradual decay of a produced charge.

3. Use of the Piezoelectric Multicomponent Transducer in Measuring Technology

The accuracy of measurements performed with multicomponent transducers is determined essentially by the means of transmitting the force to the measuring chamber. This circumstance may be the reason why piezoelectric measuring techniques have not found more widespread application. But the problem of precise force transmission could be solved by design changes and improvements in the measuring elements themselves and by the use of proved equipment setups. Since the piezoelectric technique has a significant advantage over other traditional methods in that it can measure rapidly- and strongly-fluctuating forces, piezoelectric transducers are particularly suited for analyzing physical processes which are characterized by rapid changes. A typical example of rapidly changing forces is the machining process between the tool and workpiece during drilling, milling and turning. Thus, it was the development of multicomponent transducers specifically for use in the machine-tool industry that provided the initial impetus for the application of piezoelectric measuring technology. As a result, multicomponent transducers for machining applications are currently available in the form of compact systems with measuring platforms. Thus, by combining the measuring element with a mounting, a finished measuring instrument was created.

Similar "compact systems" were developed for other applications, such as a biomechanical measuring platform for recording the reaction forces exerted on the subsoil by persons in motion.

Aside from the possibility of mounting objects to measuring platforms and recording the forces exerted on the mounting when the object is subjected to flow past it, piezoelectric multicomponent force-measuring devices have been little used in the field of fluid mechanics. The reason for this lies in the exacting requirements placed on a special setup for measuring the fluid force components of interest. The setup must first be developed and then carefully calibrated.

Setups for measuring several force components in fluid mechanics have been developed using resistance strain gauges [6, 7], but piezoelectric devices have rarely been employed. However, the frequency-resolving power of traditional resistance strain gauges is inadequate for many applications, such as the rapid force changes associated with structural vibrations due to flow, especially if the natural frequency of the measuring system is relatively low. Moreover, the use of resistance strain gauges, even those based on semiconductor technology, for the measurement of forces requires a displacement and is therefore unsuitable for investigating fluid forces on "rigid" bodies.

4. Example of the Use of Piezoelectric Multicomponent Transducers in Fluid Mechanics for the Measurement of Fluid Forces Acting on a Circular Cylinder

4.1. Statement of Problem

Consider a structure which consists basically of a framework of cylindrical members and is situated in a flowing medium. Of particular interest in the design of such structures are the flow-related stresses which could lead to structural vibrations. Based on the non-steady-state flow separation processes behind cylinders, fluid forces are created both in the direction of flow as well as normal to the flow and to the cylinder axis. The fluctuating components are distributed over a broad frequency range [8-11] and are of critical importance in the design of frameworks, cooling elements, pillars, dams, flues, masts, towers and other structures in a flowing medium.

To investigate these flow processes, we mounted a circular cylinder in a closed water channel, at right angles to the channel axis. The goal was to measure the time course of the fluctuating resistance forces K_W and the transverse forces across the channel K_Q acting on a moderately rigid cylindrical section by means of piezoelectric transducers. The circular cylinder was arranged in three sections: two lateral holding sections ("holding cylinders") and a central test section ("test cylinder"). The section designated for force measurements was located a sufficient distance from the walls of the channel to exclude "wall effects" (Fig. 2). The following requirements were placed on the measuring system:

-- It should measure the forces acting on the cylinder, both the instantaneous fluctuating values as well as rms values.

-- The test cylinder should be "rigidly" mounted.

-- The force fluctuations should be analyzed over a broad range of frequencies.

-- Despite the relatively long time required to adjust a desired state of flow, "quasi-static" force measurements should be possible.

-- The setup should be sealed to withstand a water pressure of 10 m H_2O.

4.2. Measuring System

Two 3-component piezoelectric elements (Kistler, type 9251) were chosen for measuring the forces acting on the test cylinder. From their dimensions, a cylinder diameter of D = 65 mm was arrived at.

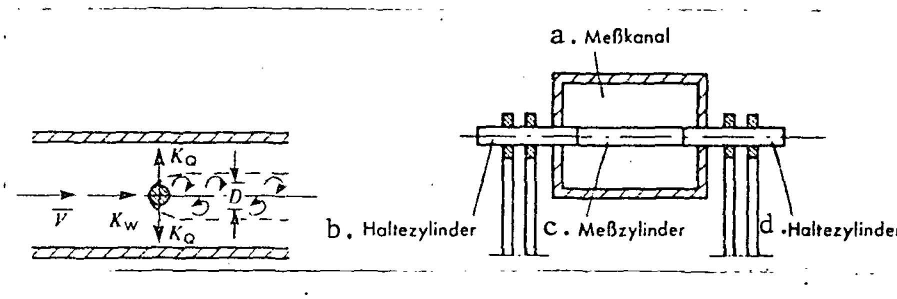

Fig. 2. Diagrammatic sketch of the circular cylinder in the test channel.

Key: a - Test channel; b - Holding cylinder; c - Test cylinder; d - Holding cylinder.

The test cylinder is mounted on each side in a bearing plate (see Fig. 3), which can be pressed against the 3-component element and holding cylinder by means of a draw rod. The fluid forces on the test cylinder are transmitted by shear to the measuring element, which is why the element must be restrained from lateral slippage by the draw rod. The holding cylinders are mounted in a /43 frame which rests upon a special vibration-free foundation (Fig. 4).

Since only dynamic measurements are possible with piezoelectric elements due to the continuous loss of charge, a "static" force measurement is possible only during a relatively short period and immediately at the onset of the load. For this purpose the measuring elements must be suddenly and simultaneously pressed against both holding cylinders at a particular point in time. The contact pressure should be about six times the fluid forces on the cylinder due to the material properties of the measuring elements. This sudden, simultaneous and relatively high pressure

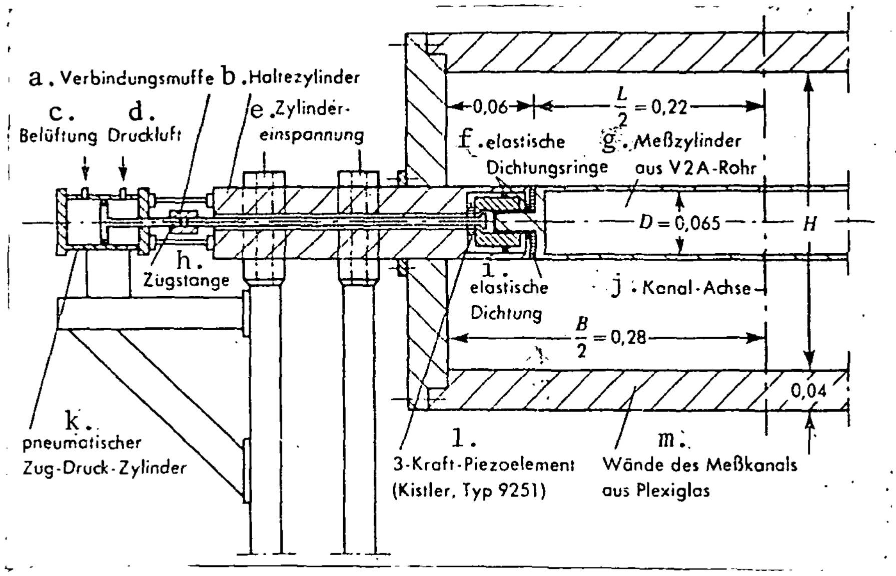

Fig. 3. Diagrammatic sketch of the force-measuring setup.

Key: a - Connecting sleeve; b - Holding cylinder; c - Air; d - Compressed air; e - Cylinder clamps; f - Elastic sealing rings; g - Test cylinder (V2A tube); h - Draw rod; i - Elastic seal; j - Channel axis; k - Pneumatic tension-compression cylinder; l - 3-force piezoelectric element (Kistler, type 9251); m - Plexiglas channel walls.

is achieved with the aid of two pneumatic tension-compression cylinders. With the control system developed, it is possible to transmit a contact pressure of 700 kp to each of the measuring elements simultaneously within one second through the tension-compression cylinders via the draw rods.

During the time in which the elements are not pressed against the holding cylinders, the test cylinder is supported by the holding cylinders by means of an elastic sealing compound (Fig. 5).

Several experiments were done under cylinder load conditions to test various types of elastic sealing compounds for their ability to produce a homogenous and watertight connection between the fixed cylinder sections and the test cylinder. On the one hand, the elastic mounting should not permit the loaded and unprestressed test cylinder to slip to the extent that disturbances are produced in its flow separation region; on the other hand, the sealing compound must not be so rigid as to prevent fluid forces from being freely transmitted to the measuring chamber. The sealing problem was finally solved by using Gurisil 550.12 sealing compound from Lonza Werke GmbH.

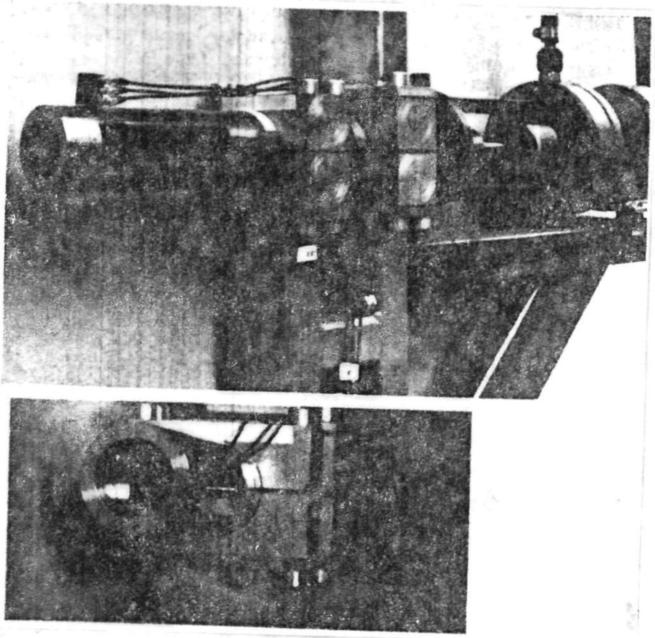

Fig. 4. Three-component Kistler type-9251 piezoelectric elements, installed.

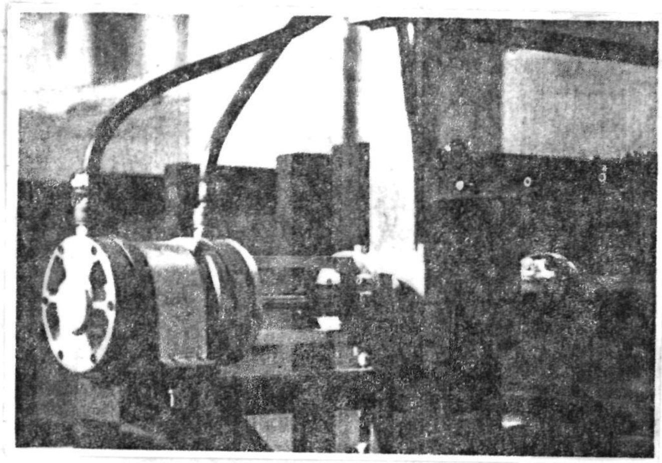

Fig. 5. Cylinder installed in test channel.

Cable connections were sealed with thermoshrink tubing and silicone rubber.

4.3. Calibration

The measuring system was calibrated separately for each force direction by the application of known forces to the test cylinder. In doing this, it was found that forces were transmitted to the holding cylinder bearings uniformly on both sides. The mutual influence between the different force components did not exceed about 1.5%. The linearity lay in a range of ±2%, which was appropriate for the limit of error. The natural frequency of the system was measured at 1500 Hz and thus occupied a range outside the force-fluctuation frequencies between 1 and 100 Hz.

The reliability of the measuring system was tested repeatedly, and it was found that the transmission of force from the test cylinder to the piezoelectric elements was reproducible.

The time constant T_g for quasi-static measurements is obtained from the relation $T_g = R_{ig} \cdot C_g$, where R_{ig} is the insulation resistance at the input of the charge amplifier and C_g is the capacitance of the feedback capacitor. In the most sensitive measurement range of the amplifier, the smallest value of $C_g = 10$ pF and $R_{ig} = 10^{14}$ Ω. This gives a time constant of $T_g = 10^{14} \cdot 10 \cdot 10^{-12} = 10^3$ sec. The anticipated measurement range is at 100 to 1000 pF, giving a T_g value between 10^4 and 10^5 sec. Now if a maximum error of 1% is allowed on the basis of self-discharge, we obtain a maximum measuring time of 100 to 1000 sec for quasi-static measurements under the conditions described. /44

4.4. Data Acquisition and Evaluation

The factors of primary interest in the flow processes discussed are the fluctuations of force in the flow direction (K_W), perpendicular to the flow direction (K_Q), their correlation with each other, and their frequency behavior as a function of flow velocity.

As the block diagram in Fig. 6 shows, the instantaneous value of the force components can be displayed on a 2-beam storage oscillograph in any desired combination with the aid of a switch. The initial stressing forces in the axial direction of the cylinder are monitored with an auxiliary indicator.

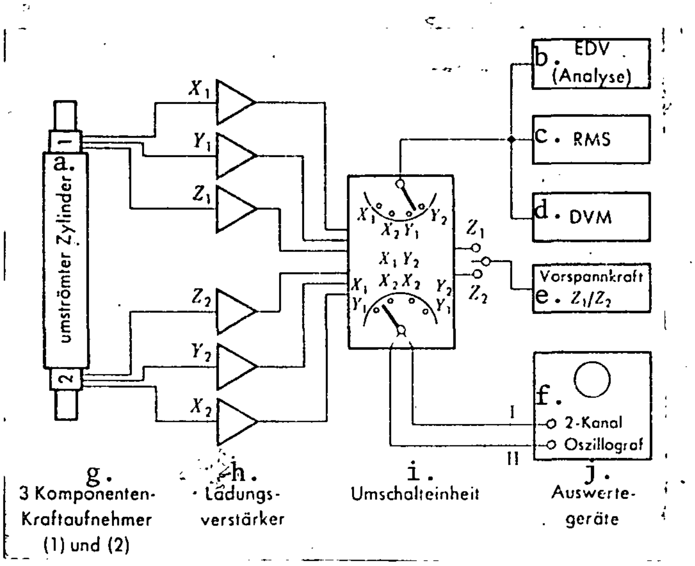

Fig. 6. Block diagram of measuring setup.

Key: a - Cylinder in flow; b - EDP (analysis); c - Recorder; d - Magnetic tape; e - Initial stressing force Z_1/Z_2; f - 2-channel oscillograph; g - 3-component transducers 1 and 2; h - Charge amplifier; i - Switching unit; j - Evaluation equipment.

Three parallel outputs also make it possible to compute mean values of force fluctuations parallel and normal to the flow direction, to record them over a certain time period with a recorder, or store them on magnetic tape so that they can be transformed and analyzed by frequency as needed. The frequency spectrum can also be obtained on-line with the aid of an analyzer.

An example of the time course of force fluctuations in the x- and y-direction is presented in Fig. 7.

5. Summary

The property of piezoelectric elements to resolve even the smallest force fluctuations and record very large load cycles almost without displacement could be applied to more technical disciplines. Rapidly-changing force fluctuations like those occurring in vibrational processes can be accurately traced through the suitable use of piezoelectric multicomponent force-measuring devices.

The sample application described here, in which piezoelectric multicomponent force-measuring devices are used in fluid mechanics, is intended to encourage the utilization of the advantages of

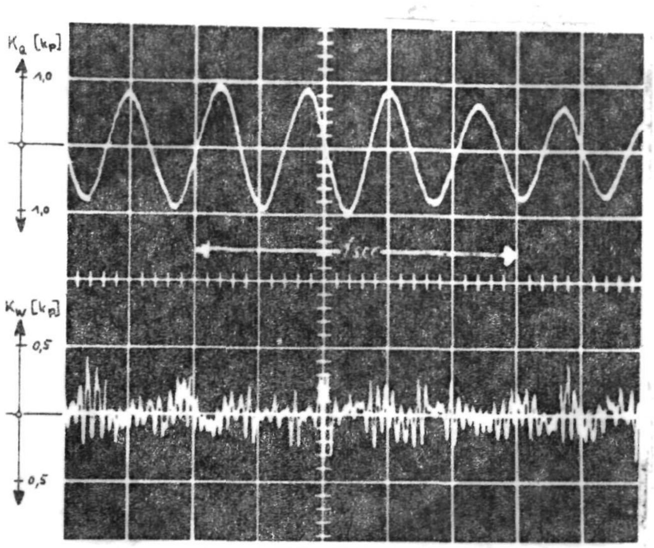

Fig. 7. Example of the time course of the transverse force K_Q and resistance force K_W.

piezoelectric technology in other areas. Though these advantages are generally known, they have not been fully utilized due to the time-consuming problem of developing corresponding measuring systems.
The extreme precision with which forces must be transmitted to the measuring elements represents another obstacle. The object of the present report is to offer one example of the use of piezoelectric multicomponent force-measuring devices in an unconventional application.

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STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-75444		

4. Title and Subtitle	5. Report Date
USE OF PIEZOELECTRIC MULTICOMPONENT FORCE MEASURING DEVICES IN FLUID MECHANICS	September 1979
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
A. Richter and K. Stefan	
	10. Work Unit No.
	11. Contract or Grant No. NASw-3199
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063	13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Anwendung piezoelektrischer Mehrkomponenten-Kraftmesser in der Strömungsmechanik," Archiv für technisches Messen/Messtechnische Praxis, No. 446, March, 1973, pp. 41-44 (A73-27871)

16. Abstract

The characteristics of piezoelectric multicomponent transducers are discussed, giving attention to the advantages of quartz over other materials. The main advantage of piezoelectric devices in aerodynamic studies is their ability to indicate rapid changes in the values of physical parameters. Problems in the accuracy of measurements by piezoelectric devices can be overcome by suitable design approaches. A practical example is given of how such devices can be utilized to measure rapid fluctuations of fluid forces exerted on a circular cylinder mounted in a water channel.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	15	