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An Ultrasonic Absolute Power Transfer Standard

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In response to increased interest in the use of calibrated sources of ultrasonic energy, we have developed a system comprising components grouped to facilitate the accurate transfer of calibration. Electronic circuitry supplied with and built into each ultrasonic transducer obviates both the use of not-readily-available radio-frequency equipment and the measurement of anything more exotic than dc voltage. Prototype transducers have shown good output at frequenices up to 78 MHz. Units now available to the public can be calibrated at output powers ranging from 5 mW to 500 mW at frequencies between 1 and 20 MHz.

Key words: transfer calibrations; ultrasonic power standards; ultrasonic transducers.

1. Introduction

Among the numerous ways in which ultrasonic transducers might be characterized, [1,2],[1] methods involving total radiated output power are outstanding both for conceptual elegance and for relative ease of implementation. Additional motivation for the use of measurements of total output power to describe the behavior of ultrasonic transducers derives from the needs of such diverse applications as medical ultrasonics and quantitative nondestructive testing. Recent increases in the use of medical ultrasonic procedures have dramatically augmented the importance of dosimetry, and thus of basic power measurements.

A method used for some time at NBS involves the determination of transducer output power from the radiation force, [3]. With our apparatus, the measurement of radiation force depends ultimately on readily-verified knowledge of the transfer characteristics of a magnetic driver. Transfer of the calibration of our radiation force balance to other power-measuring instruments is done using standard source transducers such as those developed at NBS. Given only the very realistic assumption of good long-term transducer stability, levels of ultrasonic power output can be reproduced almost as accurately as measurements of the applied rf voltage can be made and later repeated. In the event that the input voltage and output pressure of a transducer are proportional, use of a coefficient of proportionality for a particular frequency allows the generation of arbitrary power levels. A series of air-backed half-wave resonant quartz standard transducers developed for this purpose and characterized by an appropriate coefficient, the radiation conductance, has proven to be both convenient and useful. Results of extensive international tests of this series of transducers have recently been reported [4]; all quantitative aspects were consistent with expectation.

This report describes a new ultrasonic power calibration system developed as a result of further investigation of the limitations of the previous design, and in response to the needs revealed by consultation with past and potential users of standard ultrasonic sources.

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[1]Figures in brackets indicate literature references at the end of this paper.

2. Distinctive Features of the New System

Several avenues have been available for the transfer of NBS measurements of ultrasonic power. A calibration service featuring either our radiation force apparatus or a calorimeter [2], as appropriate, offers measurements on transducers alone or in tandem with their driving electronics. For the purpose of calibrating systems for ultrasonic power measurements in other laboratories, NBS standard sources are available for loan in consideration of a fee for their recalibration upon return. It is this latter application which is addressed by our new system. The new system reduces and simplifies the effort required of the user. By allowing for operation at several frequencies, the design of the new transducers substantially reduces the amount of equipment required to cover a given frequency span.

Radio-frequency energy for continuous-wave ultrasonics work is usually derived from a signal generator (oscillator or synthesizer) driving a power amplifier. Since the electrical impedance of a typical standard source departs widely from the 50 ohm output impedance of the usual power amplifier, the interests of economic and electrical efficiency dictate the use of an impedance-matching network between power amplifier and transducer. Under most circumstances of operation, the impedance of our new standard source is outside the operating range of matching networks known to be commercially available. Attempts to use matching networks of conventional design to drive the new source result in low overall efficiency (a few percent) and consequent severe overheating of the matching network. These problems are avoided by providing suitable matching networks of customized design with each transducer. Our networks employ a small module interposed between the transducer and connecting cable, and a conventionally-adjustable unit between the connecting cable and power amplifier.

Another problem encountered in the field involves measurement of applied rf voltage. Substantial errors can arise both from circulating currents outside interconnecting cables and within nearby metallic apparatus, and from the use of insufficiently short cabling between transducer and voltmeter. Circulating currents cannot easily be anticipated nor controlled, while the physical configuration in many applications involving submerged use of a standard source precludes the use of short cabling. These onerous contingencies are circumvented with our new system by the inclusion of voltage-measuring circuitry inside the transducer itself. A proportional dc signal is carried from the transducer in the same conductor carrying rf excitation to the transducer; an external splitter inserted anywhere between the transducer and the matching network allows connection of a dc voltmeter. This arrangement is shown in figure 1. In this application only the precision and stability of the metering circuit are important; accuracy and linearity are of secondary importance as design criteria. Component values are chosen to optimize the precision attainable with a particular dc voltmeter range over the intended ultrasonic power range. Typical values for isolation resistors R_1 and R_2 are 10 megohms when a dc voltmeter of 10 megohm input resistance is used. Divider capacitors C_3 and C_4 typically range from 10 pF to 100 pF. A 5000 pF capacitor serves as bypass capacitor C_2. Silvered mica capacitors and metallized film resistors are used throughout. In addition to eliminating the possibility of errors inherent to the use of external rf-measuring equipment, the use of built-in metering allows the transfer of rf voltage measurements with improved accuracy; the same device can be used by both NBS and the user to reproduce predetermined voltage

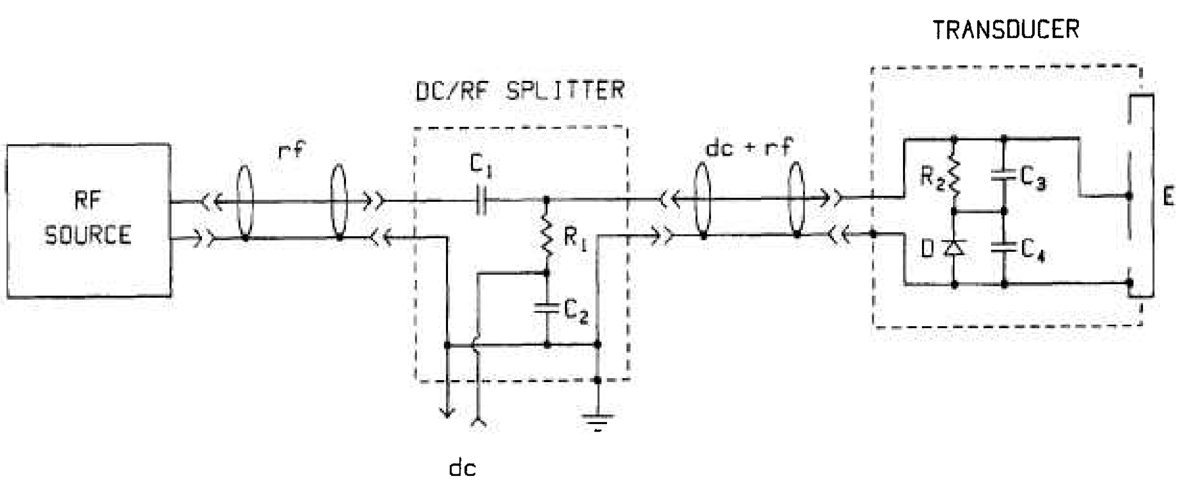

Figure 1—Interconnection of system components.

levels with accuracy limited only by the dc voltmeters used. This procedure allows the transfer of NBS measurements of output power to be effected directly, without use of a derived radiation conductance. It is expected that use of this direct procedure will offer a significant improvement in the overall accuracy of calibration transfer. (The present estimate of uncertainty for measurements of radiation conductance is 3% to 8%, increasing with frequency.)

3. Distinctive Features of the New Transducer

The configuration chosen for the transducer unit (fig. 2) shares with its predecessors from NBS the use of a 2.54-cm-diameter coaxially plated piezoelectric element. In the interest of durability, the metal-plastic composite case material used earlier has been replaced by stainless steel. The overall length of the unit has been reduced to less than 12 cm including the electrical connector. The possibility of unwanted electrical coupling between the transducer and its surroundings (e.g., metallic mounting fixtures) has been diminished by the incorporation of a feature which avoids the flow of current in the transducer housing: three isolated internal wires connect the inner surface of the "wrap-around" ground electrode to the outer shell of the BNC connector. Electrical isolation of the crystal element is preserved by the use of a formed-in-place silicone rubber support for the element. The use of compliant mounting is intended to foster stability of performance by minimizing coupling of unwanted possible modes of ultrasonic vibration from the crystal element to the housing, loading of the crystal element by the mount, and the application of static stresses to the crystal element. Overall control of the mechanical environment of the transducer element is much improved in comparison to that of earlier designs. Because of the paucity of suitable waterproof connectors, a standard BNC connector is used and it is left to the user to provide the waterproofing necessary for submerged operation. In practice this is accomplished easily by stretching appropriately-sized surgical tubing over the end of the transducer. The option of providing a permanently-attached cable was rejected to simplify construction, to provide the user with greater operational flexibility, and to allow the rf connector to also provide atmospheric venting of the transducer during storage and shipping.

Although special-purpose units with other fundamental frequencies will be made available as needed, the general-purpose standard source intended to fit most applications will have a nominal fundamental resonance at 0.5 MHz. This choice allows odd overtone operation at output frequencies spaced 1 MHz apart, so that one transducer can suffice in many applications involving wide-band calibrations. Constraints on connecting cable size and breakdown voltage, and on size and complexity of the accompanying matching network dictate the use of a transducer element material of higher coupling constant than that of quartz. (In the present geometrical configuration, quartz elements of fundamental resonance below 2 MHz require impractically large drive voltages at higher power levels of interest. Also, harmonics spaced 4 MHz or more apart limit the usefulness of overtone operation.) Lithium niobate in the 36 degree Y-cut was chosen for use in our new transducers since, at a given resonance frequency, a transducer using lithium niobate requires approximately 5% of the drive voltage needed to obtain the same ultrasonic output power from a quartz transducer element. Tests of five prototype transducers have confirmed this and other favorable expectations. Stability of the lithium niobate transducers, as indicated by measurements of radiation conductance, has so far been indistinguishable from that

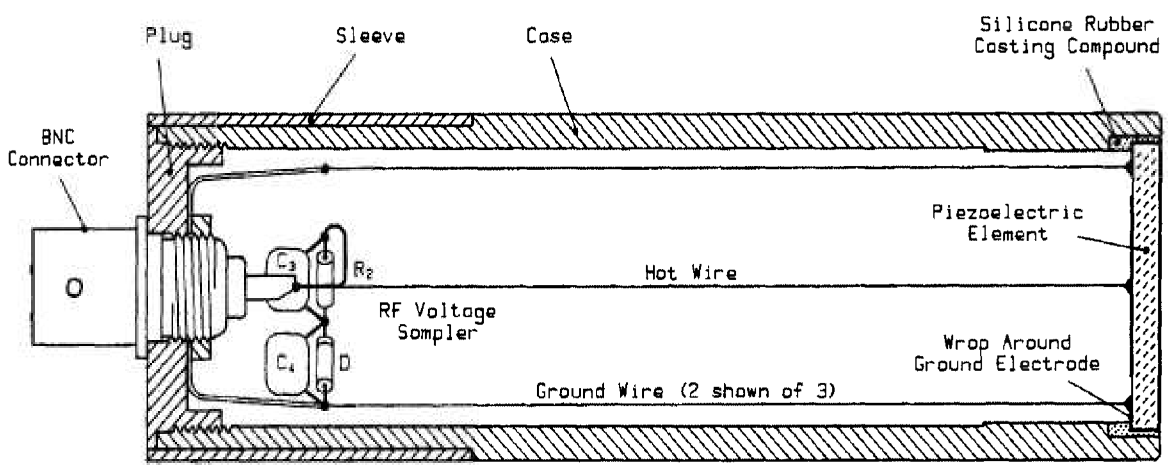

Figure 2 – Longitudinal section of standard ultrasonic source.

of quartz transducers. Performance of the new transducers at overtone frequencies has been checked by both spot and swept-frequency tests. It has been found that good output is readily obtained at frequencies well above those needed by most users. Figure 3 shows the result of a swept-frequency measurement from 1 to 30 MHz. In this test, the error signal from the radiation force balance [3] was recorded while the transducer drive frequency was slowly increased; a crystal diode pickup connected at the transducer terminals was used to monitor input voltage to the transducer. Although this arrangement does not provide absolute measurements of output power [3], the test suffices to show that ample output can be obtained at high frequencies. The upper frequency limit for this experiment was determined by the test equipment. In other tests, similar output levels have been obtained at frequencies up to 78 MHz. Comparison of the data for transducer output power and transducer input power (as indicated by the square of the input voltage), has indicated that the decrease in output with increasing frequency cannot be attributed solely to decreasing drive voltage. Radiation force balance measurements of absolute power at spot frequencies up to 21 MHz have established that, despite the presence of additional loss mechanisms, at least one watt of indicated output can be obtained.

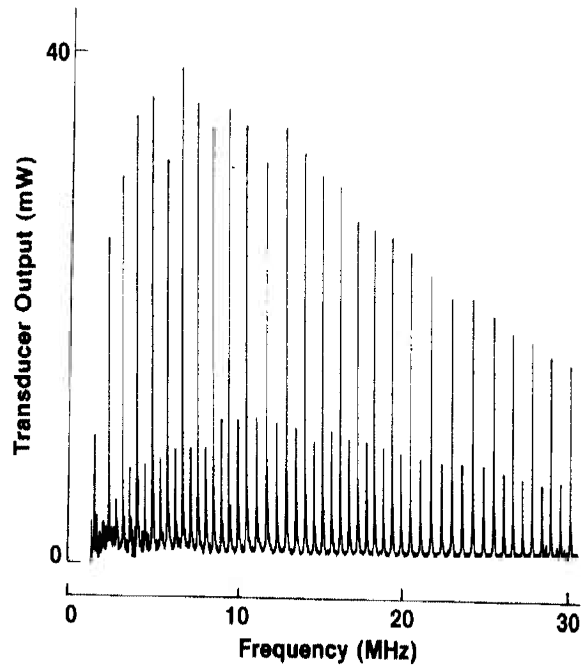

Figure 3 – Swept-frequency response of 0.5 MHz prototype transducer.

4. Conclusion

Design and operational details have been presented for a new system for ultrasonic power calibrations. Improvements over earlier versions include the mechanical design of the transducer and the provision inside each transducer of circuitry for measuring the applied voltage. This feature fosters improved accuracy by eliminating a radio-frequency measurement of voltage (replacing it with a dc measurement) and by reducing the number of computations needed for the overall procedure. Both the ease of use and the range of power levels attainable are increased by the availability in the new system of an impedance matching network of customized design. The use of a different material, lithium niobate, for the piezoelectric elements allows lower losses in the driving electronics, and more importantly, allows a lower fundamental resonance (0.5 MHz) than was previously used. This in turn allows overtone operation at convenient 1 MHz intervals. Because of its capability of multifrequency operation at such closely-spaced frequencies, the new transducer is "universal" in that one unit can replace several older units, each suitable only for single-frequency operation.

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