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6. AUTHOR(S)

Julian D. Maynard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Pennsylvania State University
Department of Physics
104 Davey Lab
University Park, PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER

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13. ABSTRACT *(Maximum 200 words)*

The goal of this project is to explore novel configurations of heat exchangers and the stack (heat pumping) section of thermoacoustic heat engines. The approach will be to use anisotropic systems, such as made possible by glass capillary array technology. A part of the project will involve the development of high power drives and acoustic resonators for testing the new systems.

DTIC QUALITY INSPECTED

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20. LIMITATION OF ABSTRACT

ANISOTROPIC HEAT EXCHANGERS/STACK CONFIGURATIONS FOR THERMOACOUSTIC HEAT ENGINES

This report summarizes the goals and accomplishments for ONR grant N00014-93-1-1127, "Anisotropic heat exchangers/stack configurations for thermoacoustic heat engines". The goals are a) to explore various technologies, such as glass capillary arrays, for use as combined, anisotropic heat exchanger/stack systems, and b) to develop high power drives and shock-avoiding acoustic resonators for testing the new systems.

General developments

A basic problem encountered during the past year was that the funds arrived too late for acquiring a graduate student to work on the project; by the time it was known that the project would be funded, all students had to be accounted for financially. Fortunately, we were able to enlist the help of a capable undergraduate student, who developed a prototype of a high power acoustic drive and documented his work in a senior honors thesis. A patent for this drive system has been submitted; a discussion is presented in the next section.

Modified high speed (20,000 RPM), large displacement (13 cm^3) model aircraft engines have been ordered for use in linear acoustic resonators which will be used to test the new heat exchanger/stack systems. A company, Collimated Holes, Inc. has been contacted for advise in fabricating glass capillary arrays. A new graduate student has just joined our group to work on the heat engine project.

Development of a High Power Drive for a Thermoacoustic Heat Engine

While most applications of oscillatory drives require modest power levels (e.g. less than 1 kilowatt in acoustic applications), tests and applications of thermoacoustic heat refrigerators might require high power levels (e.g. many KW) and large displacements (on the order of centimeters, or acoustic Mach numbers as large as 0.1). High power, large displacement drives may be made with cranks, cams, unbalanced loads, etc. Such drives are usually limited to relatively low frequencies; for oscillatory motion, acceleration and force are proportional to frequency squared, with the result that higher frequencies place excessive loads on crank or cam bearings. High power drives for higher frequencies are typically electromechanical "shakers", which employ coils of wire positioned, with compliant suspensions, in high magnetic fields. High power densities are achieved by establishing the static magnetic field with permanent magnets made from state-of-the-art ferromagnetic materials. These devices are limited by the critical Joule power dissipation of the wire in the moving coil, above which the wire fuses. This problem is particularly restrictive in oscillatory devices, because in this case the coil spends much of the time at or nearly at rest, and there is no electromotive force (emf) induced back into the coil to limit Joule power dissipation and heating. In an electric motor, the armature coils are constantly in motion, and the induced back-emf prevents catastrophic Joule heating in the coil.

We proposed that oscillatory drives might be built using the rotary motion of motors, and converting the rotary motion to oscillatory motion using only permanent magnets. For

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an electromechanical drive, electric motors would be used, and since the coils would be in constant motion, the problem of coil wire fusion would be alleviated. In general, the non-contact nature of forces between permanent magnets in converting rotary motion to oscillatory motion would circumvent problems of wear for crank bearings, cams, etc. The method would permit high drive powers because of the high energy densities available with state-of-the-art permanent magnets. Readily available magnets have energy densities of 2.5×10^5 joule/m^3. The force between two 10 cm diameter magnets would be on the order of 2000 N. If this force were used to drive an oscillator with a 1 cm displacement amplitude at 60 Hz, then the power delivered would be several kilowatts. Larger magnets, multiple sets of magnets, and higher frequencies would increase the available power proportionally, and drive powers of many kilowatts would be possible. Multiple sets of magnets could also be used to increase the frequency of oscillation for a given rotation speed of the motor. An example is described below.

A particular model for converting rotary motion to oscillatory motion using permanent magnets is illustrated in Fig. 1. The model consists of three parallel disks, each free to rotate independently on a common shaft. The middle disk is connected to springs which allow the disk to undergo torsional oscillations. The outer disks are driven by motors (or a motor and gears) in rotary motion at the same speed but in opposite directions. Each disk contains a set of magnets which are oriented so as to attract the magnets in the neighboring disk. By having N magnets equally spaced around each disk, the torsional drag between the disks is increased and the frequency of oscillation of the middle disk is N times the rotation speed of the outer disks.

The operation of the model in Fig. 1 is depicted in Fig. 2. The operation is interesting because the power delivered to the oscillating disk is a nonlinear function of its amplitude squared, as it would have been for the customary driven oscillator. Fig. 2a and 2c show angular displacements for a magnet in the oscillating middle disk (solid line) and the passages of magnets in the counter-rotating disks (dashed lines) as functions of time. Fig. 2b and 2d show the resulting force on the magnet in the middle disk as a function of time. A small amplitude case is illustrated in Fig. 2a and 2b, and a large amplitude case is illustrated in Fig. 2c and 2d.

As a rotating magnet passes the oscillating magnet in the small amplitude case (as illustrated in Fig. 2a), a force is first felt in one direction, and then as the rotating magnet passes, a force is felt in the opposite direction. This is illustrated by the passage at the center of Fig. 1a and by the bipolar peaks in the center of Fig. 2b; the counter-rotating magnet would produce the bipolar peaks at the left and right in Fig. 2b. It might be thought that the bipolar peaks would cancel, resulting in no net driving force. However, the phasing of the disks may be established so that the velocity of the oscillating disk also reverses with the force, so that the power delivered is nominally positive. However, with this phasing the maximum speed of the oscillating disk, indicated by the arrows in Fig. 1b, occurs near a minimum in the force, with the result that a relatively small amount of power is delivered to the oscillating disk.

In the large amplitude case, the amplitude and phase may be set so that the rotating magnets pass the oscillating magnet and then travel together with the oscillating magnet for some fraction of the cycle, as illustrated in Fig. 2c. This results in a force which extends through the points of maximum velocity, as shown near the arrows in Fig. 2d, and produces a relatively large amount of power delivered to the oscillating disk. The amplitude (approximately $1/2\pi$times the spacing of the rotating magnets) and phasing illustrated in Fig. 2c is optimal, and produces more than twice the power (normalized with the amplitude squared) delivered by the situation of Fig. 1a.

A version of the model described above has been constructed and tested. The test device used small cylindrical rare earth cobalt magnets of diameter 2 cm and thickness 0.6 cm, each weighing 15 gm. Because of modest tolerances in the test device, the gap between the disks was relatively large, 0.2 cm, and the resulting torsional drag between the disks was only $\sim$70 N. At the resonance frequency of the middle disk (30 Hz) the amplitude of oscillation was 0.5 cm. By measuring the quality factor of the oscillator (using the free decay of the middle disk oscillator), the power delivered to the oscillator was determined to be 33 W, in good agreement with the predicted value.

It may be noted that for the model illustrated in Fig. 1, the rotating magnets also produce an unwanted oscillatory torque transverse to the shaft. This effect may be eliminated by using a hollow middle oscillating disk with a rotating disk inside, and outer disks rotating together, but opposite to the inside disk. In this configuration the forces parallel to the shaft cancel, and the torque transverse to the shaft is eliminated.

Current and Other Funding

Other research grants include:

1. NSF Division of Materials Research, Condensed Matter Physics Program, DMR 93-06791, 249,000/3 yr, which includes 1 man-month of the principal investigators time.
2. ONR, Physics Division, N00014-92-J-1186, November 1, 1991 to October 31, 1994, 300,000/3 yr, "Innovative acoustic techniques for studying new materials and new developments in solid state physics"; includes 2 man-months of time for the principle investigator.
3. ONR, Physics Division, N00014-93-1-0779, June 1, 1993 to May 31, 1996 105,000/3 yr, "Training students in new acoustic techniques for studies of fracture and nondestructive evaluation of exotic materials"; includes 1 man-months of time for the principle investigator.

APPENDIX: OFFICE OF NAVAL RESEARCH
PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT
for
1 OCTOBER 1993 through 31 MAY 1994

R&T Number: 3126972ess02

Contract/Grant Number: G N00014-93-1-1127

Contract/Grant Title: Anisotropic Heat Exchanger/Stack Configurations for Thermoacoustic Heat Engines

Principal Investigator: Julian D. Maynard

Mailing Address: 104 Davey Lab
University Park, PA 16802

Phone Number: (814) 865-6353

E-Mail Address: maynard@phys.psu.edu

a. Number of Papers Submitted to Refereed Journals: 0

b. Number of Papers Published in Refereed Journals: 0

c. Number of Books or Chapters Submitted but not yet Published: 0

d. Number of Books or Chapters Published: 0

e. Number of Printed Technical Reports & Non-Refereed Papers: 0

f. Number of Patents Filed: 1

g. Number of Patents Granted: 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 0

i. Number of Presentations at Workshops or Prof. Society Meetings: 0

j. Honors/Awards/Prizes for Contract/Grant Employees: 1

k. Total Number of Graduate Students and Post-Docs Supported at least 25 % this year on this contract/grant:

Grad Students: 0	Post-Docs: 0
Grad Student Female: 0	Post-Docs Female: 0
Grad Student Minority: 0	Post-Docs Minority: 0

PUBLICATIONS, PRESENTATIONS, ETC.

PATENTS FILED

High Power Oscillatory Drive, submitted March, 1994

TECHNICAL REPORTS AND NON-REFEREED PAPERS

Rob Bailis, University Scholars Honors Thesis, "A Magnetic Drive Torsional Oscillator for use in a Thermoacoustic Heat Pump", The Pennsylvania State University, 1994

HONORS/AWARDS/PRIZES

Silver Medal in Physical Acoustics, to be awarded November 30, 1994

MISCELLANEOUS

Undergraduates Involved in Research:

1. Rob Bailis, Senior, 1994

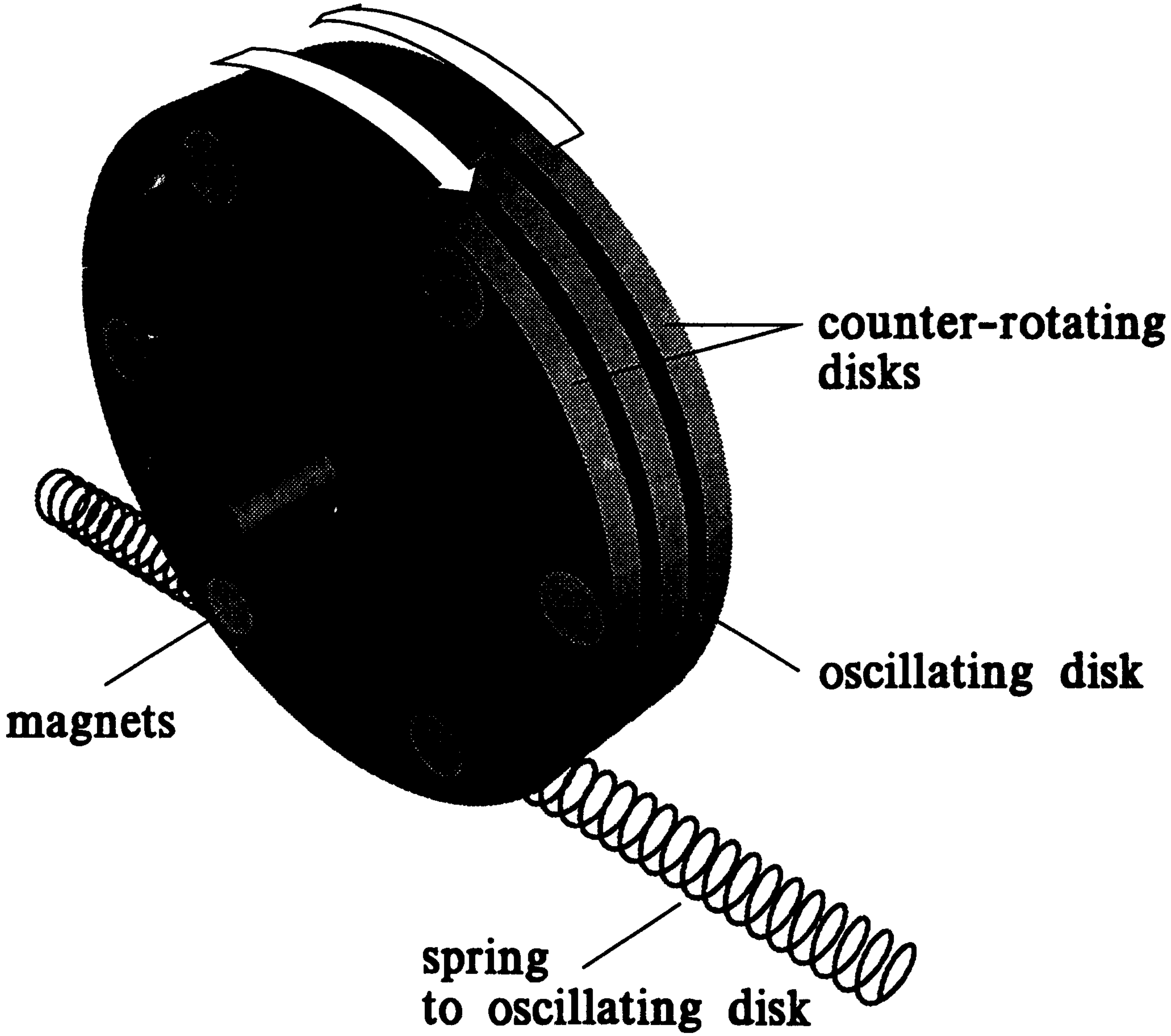
counter-rotating disks
oscillating disk
magnets
spring to oscillating disk

Figure. 1

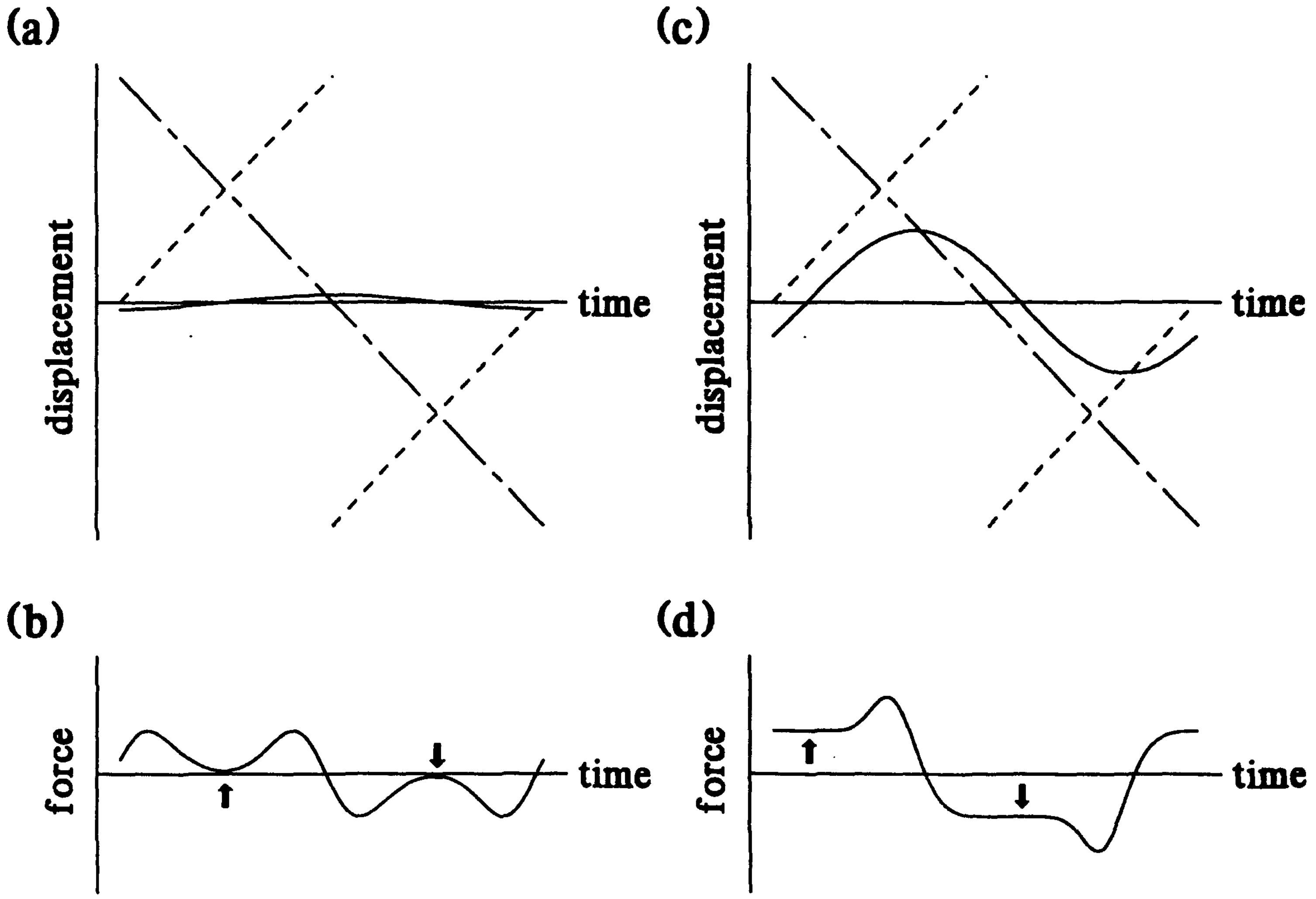
(a)
displacement
time
(c)
displacement
time
(b)
force
time
(d)
force
time

Figure 2.