Continuum Control Corporation

Compact Piezoelectric Based Power Generation

Dr. Kamyar Ghandi

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Sponsor: DARPA/USAAMC
Program Manager: Dr. R. Nowak

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Company Overview

Continuum can leverage its current technology and funding to rapidly develop new applications

- Founded in July 1998
  - Over $1M/year in R&D funding
  - 10 full-time, 5 part-time employees
- Proprietary technology
  - Pending & licensed patents
  - Proprietary manufacturing process
- Prototype products shipped to over 20 customers (US, Europe)
  - *Existing product sales*
  - *OEM Development/production contract for $2M-$5M opportunity in 2000*
- Goal: build a great company that is positioned for IPO/Acquisition in 4-5 years

Key Technical Personnel

Continuum has an experienced business and technical team

Dr. Kamyar Ghandi (Vice President, R&D)

- PhD MIT Aerospace
- Self-Powered™ co-inventor
- Principal Investigator of multiple DoD research programs

Dr. Aaron Bent (President)

- PhD MIT Aerospace
- PiezoFlex™ inventor
- Manager of multiple DoD research programs ($12M total funding)

Dr. Nesbitt Hagood (Chief Technology Advisor)

- Tenured MIT Professor
- Director MIT Smart Lab ($4M/year)

Mr. Jonathon Leehey (Chief of Electrical Engineering)

- Masters MIT
- High tech start-up experience
- 20 years of electronics design, and production experience

Mr. Richard Warnock (Chief of Composites Technology)

- Masters U. of California Mechanicalexperience
- 17 years of composites production experience

Energy Sources for Electronic Devices

Current Battery Technology Limitations

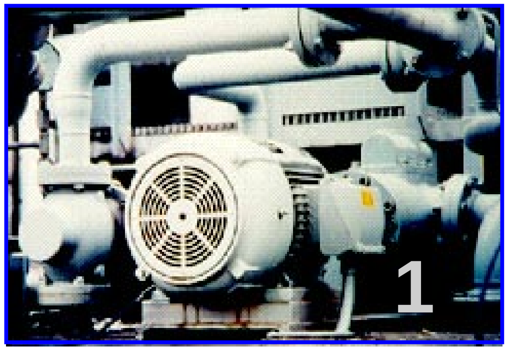
- Finite useful life
- Numerous recharging
- Back-up power sources / batteries required
- Increased expense over lifetime of the product

Alternative: Harness Natural Power

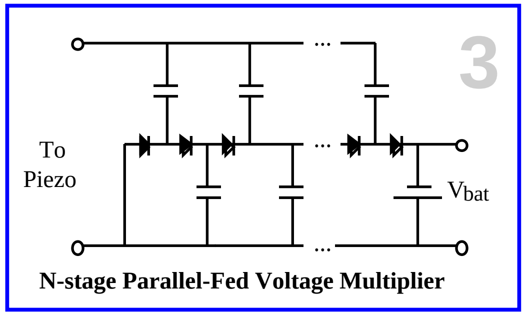
- The energy available from the environment is harnessed to create power for beneficial purposes
- Efficient use of readily-available energy
- Eliminate the need for recharging
- Provide Guaranteed Power (power is always available)
- Supplement/Replace Battery Power

Piezoelectric Power Generation - Technology Components

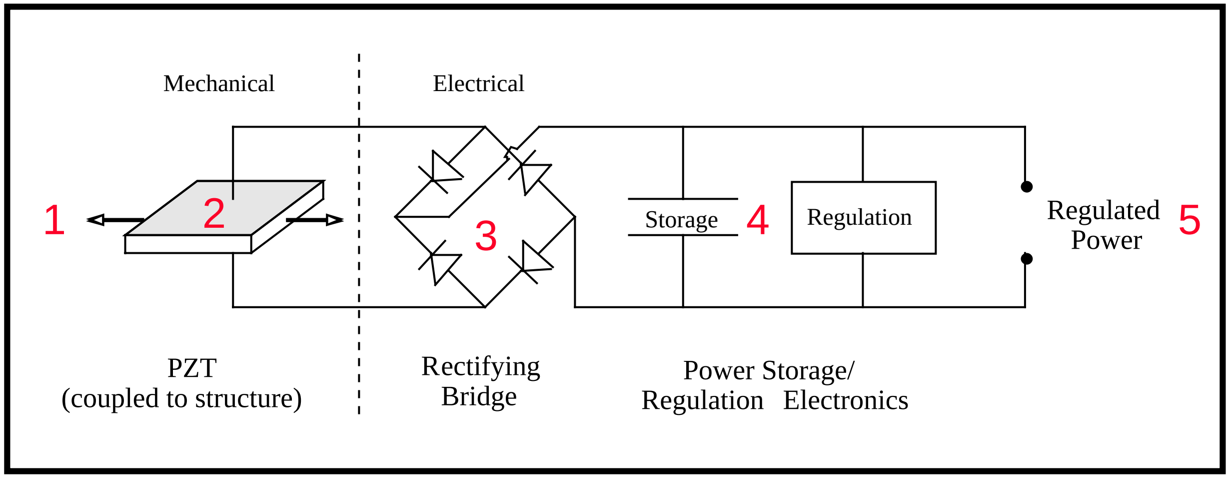
Vibration Source



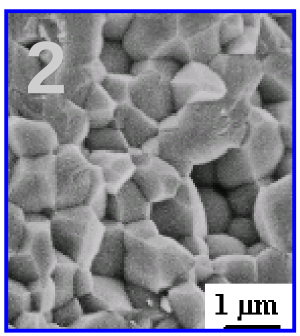
Rectifier Circuitry

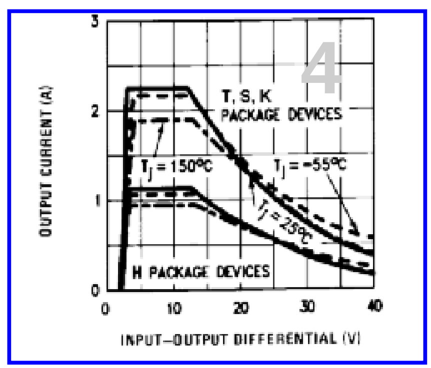


Application Load



Transduction Material





Regulation & Storage

Personal Power

Force XXI Land Warrior

Application: Powering next generation soldier suite

- enhanced navigation, radios, combat ID functions, helmet mounted displays

Load/Requirements (full suite)

- as designed: 7-8 W continuous
- near term advancements: 3 W continuous, 25 W bursts

Approach

- Heel integrated package, thickness mode operation
- capable of supplying 0.5+ watts per boot (5 cm^3) with novel electronics

System Impact

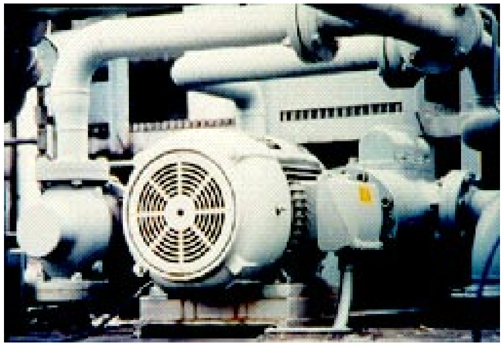
- Complete power: eliminate 2-5 lbs of batteries (for 12 hour mission)
- Partial power: several subsystems - possibly boot integrated GPS

Commercial Opportunities

- Discussions with Mototola's LandWarrior Systems group.

Maintenance/Monitoring

Vibrating Machinery



Composite Aircraft

Application: Powering remote sensors

- Condition Based Maintenance (CBM)
- Structural Health Monitoring

Load/Requirements: CBM Example

- as designed: 100 mW for sensor, conditioning, digitize
  500 mW/transmit; 250 mW/receive
- Needs in 1-2 years: 1/5th to 1/10th of above

Approach

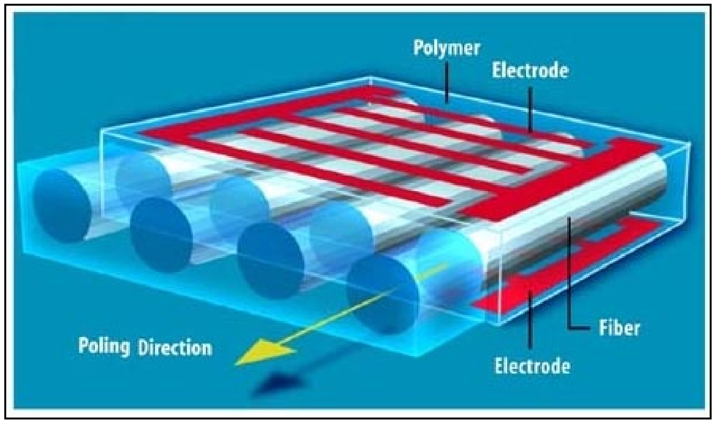
- bonded strain patch, planar mode operation
- capable of supplying 0.5W per 1.6 cm^3 material

System Impact

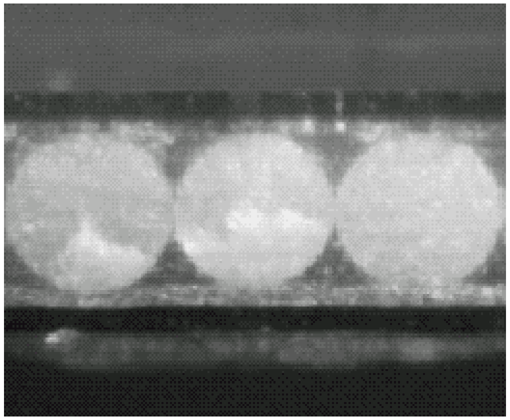
- Enabling (aircraft): distributed sensor networks in sealed parts (skin, nacelle)
- Cost Effective (CBM): compare to $1000-$5000 per wired sensor channel

Active Fiber Composite Technology

- Active Fiber Composites (AFC's) originated from work by Bent & Hagood (1992), sponsored by ONR (Dr. Wallace Smith)



- High Performance
- Directional Actuation
- Conformable
- Robust
- Large Area

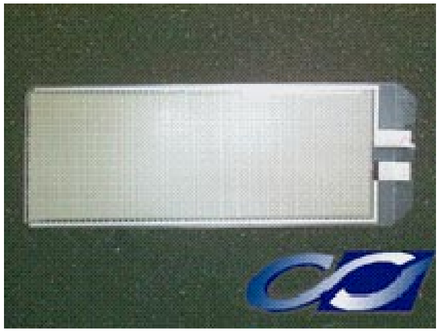


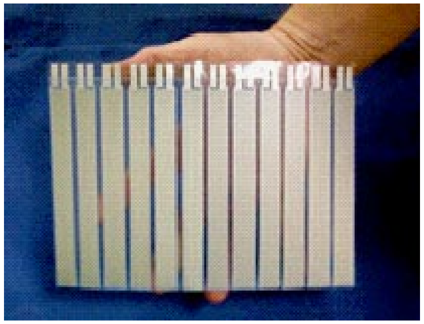
Piezoelectric Fibers:	→	*Stiffness and actuation authority*
Polymer Matrix:	→	*Load transfer mechanism*
Interdigital Electrode:	→	*Align field with fibers*
Glass Fibers:	→	*Integral reinforcement*

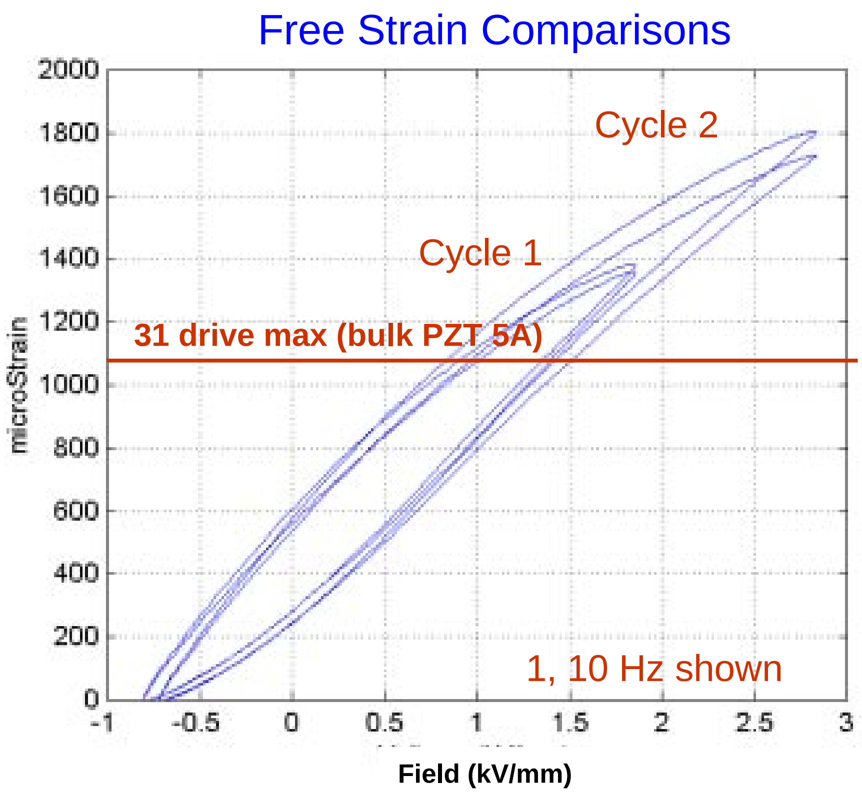
Foundation Active Fiber Composites Consortium (AFCC) effort supported by DARPA/AFOSR program under S. Wu and W. Smith

Active Fiber Composite Properties

- Recent improvements in fibers processing, composite fabrication methods, and materials have resulted in significant performance increases







2 times the strain energy density of a similar 3-1 mode monolithic piezoceramic

DARPA Energy Harvesting Program

Phase I SBIR: Tool Development

Part I: Modeling

Elements

- Analytical & simulation
- Coupled electro-mech system model
- Nonlinear elements

Objectives

- establish a design methodology
- extrapolate experimental results
- initial application feasibility

Part II: Experiment

Elements

- Simple representative system
- breadboard implementation
- diagnostic & measuring capability

Objectives

- determine system losses
- validate model
- prove harvesting is valid concept

Phase II SBIR: Application Implementation

Part I: Technology Development

- New materials evaluation
- Develop amplifier circuits
- Develop control logic & circuits
- Address battery charging issues
- Validate approach experimentally

Part II: Prototype Demonstration

(Integration for Stand-alone system)

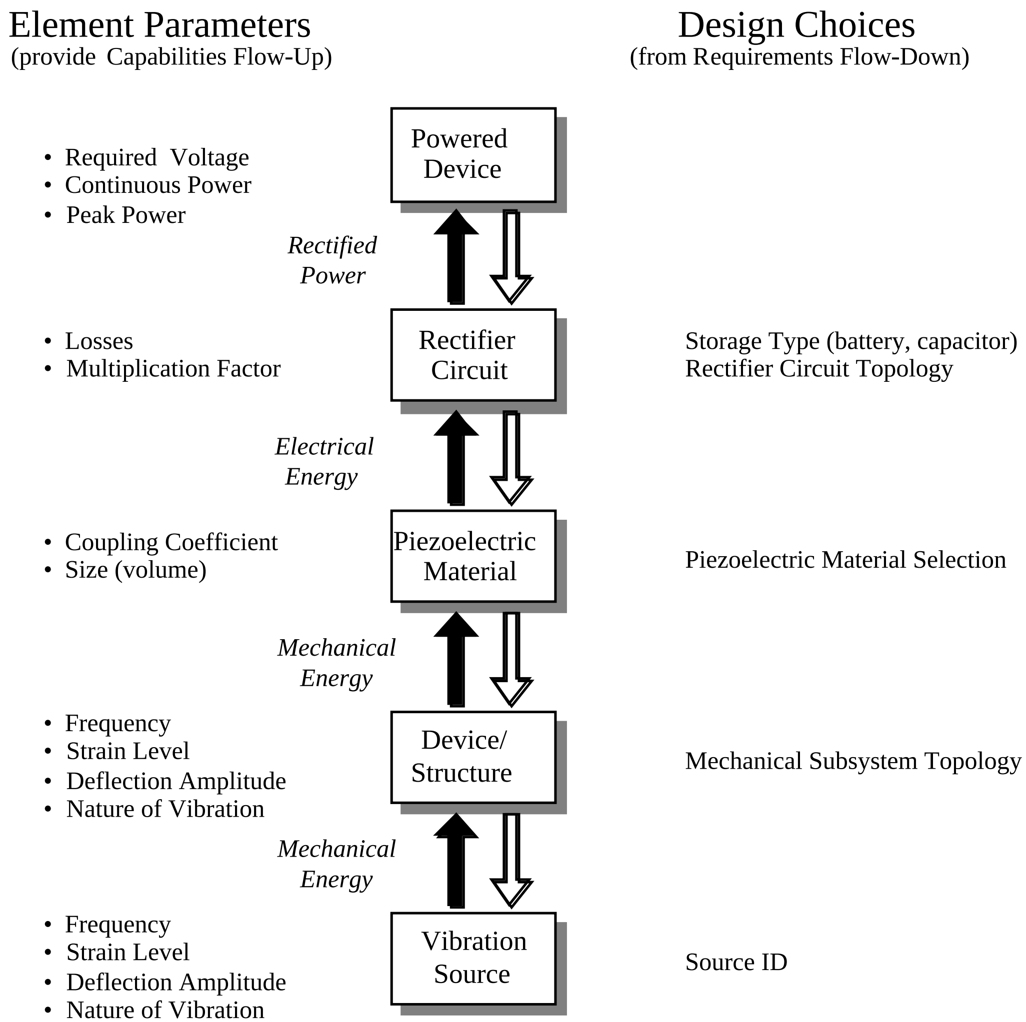
- Characterize transducer materials
- Finalize harvesting architecture
- Electrical component miniaturization & integration
- Mechanical system design
- System integration & demonstration

Systems Level Modeling/Design

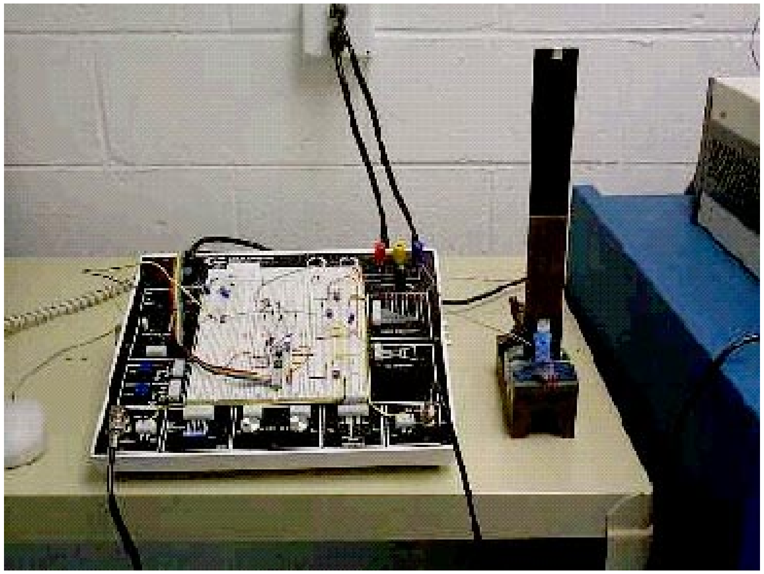
Model based design

Nonlinear simulations

- Accurate predictions



Phase I SBIR: Experimental Demonstration



Representative Testbed Structure

- Gr/Ep Beam $[0/60/-60]_S$
- 4 Piezo Packs
  - two used as disturbance source
  - two used for energy harvesting

Electronics

- Protoboard implementation
- Energy harvesting circuits
- Power monitoring circuits

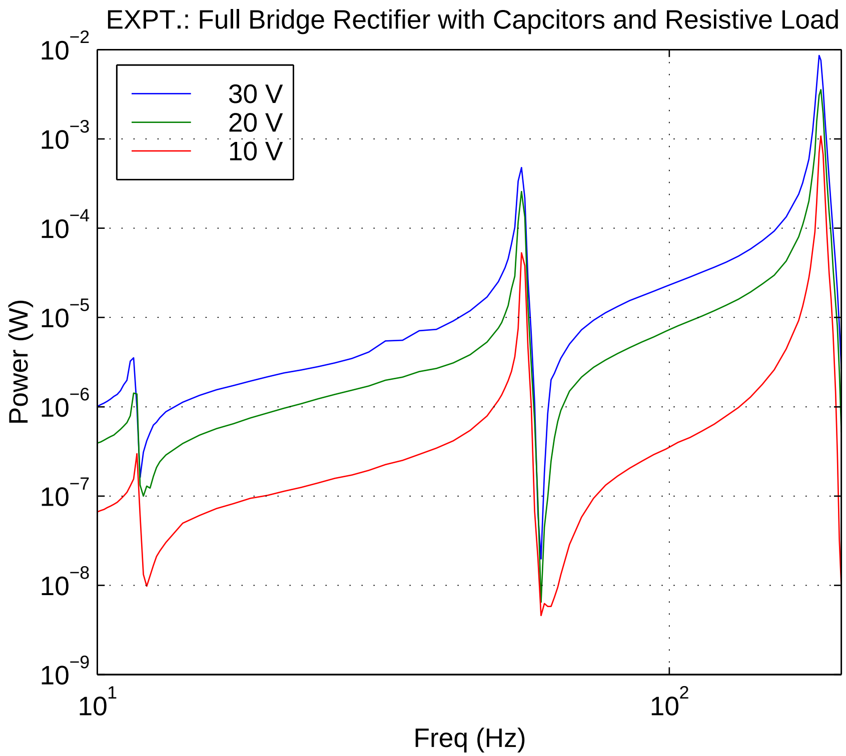
Data Acquisition System

- Developed custom National Instrument VIs
- Automated measurements during frequency sweeps

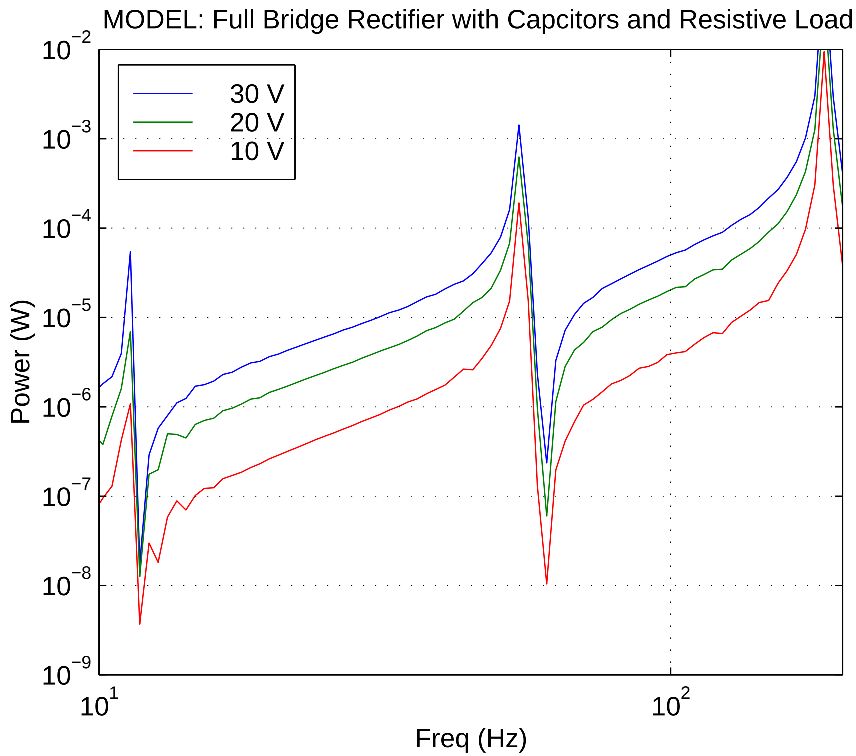
Phase I SBIR Model Experiment Correlation

- Correlated predicted power levels from Simulink model with experimental results.

Experiment



Model



- Due to complex interaction of subsystems, analysis of full system is required for comparing different circuit topologies.
- Validated model may be used to extrapolate performance of other systems

DARPA Energy Harvesting Program - Phase I Results

Development of Modeling Capability & Tools

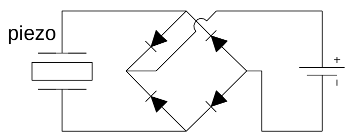
- demonstrated that complexity of system interaction requires analysis of complete system
- developed models of fully integrated structural/electrical systems, using modular approach

Phase II

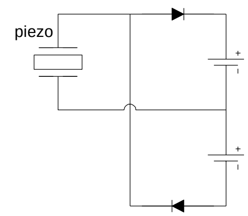
- Further analysis of additional circuit topologies
- Characterization of transducer materials under load.
- Focus on Implementation of amplifier circuit & control logic
  - Address circuit non-idealities
- Design and build energy harvesting module for a real application

Passive Rectifier Circuit Topologies

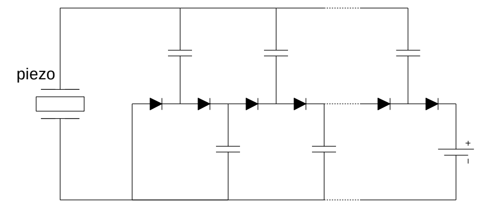
- Predictions using Analytical Model:



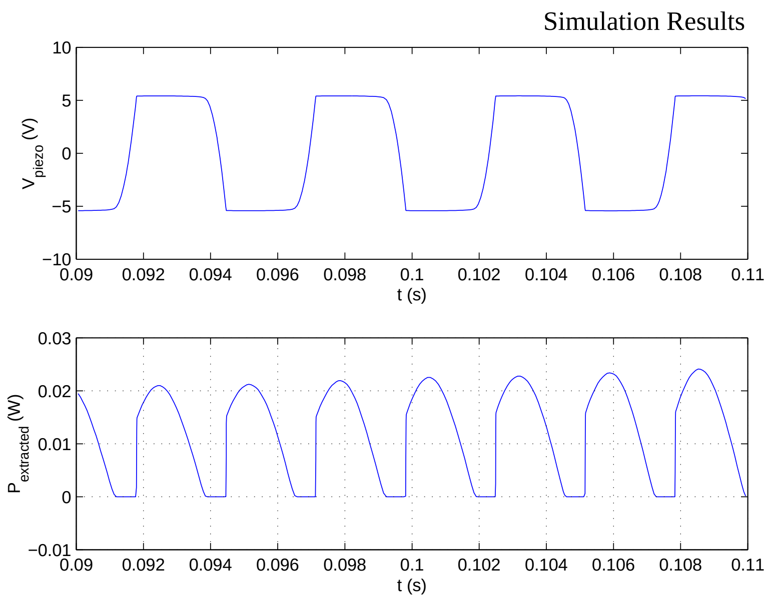
Full Bridge Voltage Rectifier

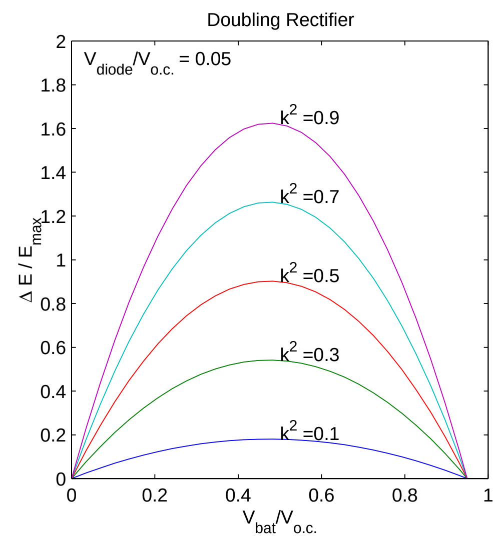


Voltage Doubling Rectifier



N-stage Parallel-fed Voltage Multiplier





- Optimum circuit for reducing diode losses: Voltage doubling rectifier.
- Optimum battery voltage for maximum power: 1/2 open circuit voltage

Predictions - Heel Strike

Compute electrical power levels derivable from the boot heel strike.

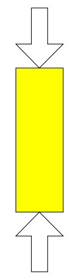
Load environment

- 100 kg soldier walking at 1Hz.
- Output Power

A) Direct forcing of a piezoelectric stack.

Transducer Thickness: 2 cm

Transducer Area = 0.16cm^2 (0.4cm x 0.4 cm)



- Note: Stress on transducer should be maximized for best performance.

CASE A		PVDF(irad)	PVDF	PZT-4	PZT-5A	PZT-5H	Single Crystal
Deflection	um	288.00	683.71	5.15	5.94	5.64	9.60
Volage Levels (10m)	V	88.24	157.90	7.85	7.76	6.16	12.02
Pasive Power	mW	12.3	5.4	2.3	2.9	3.7	26.5
Active Power	mW	122.5	53.7	22.7	29.0	36.5	264.5

Freq = 1Hz, Stress = 31.3MPa, Area = 0.16cm^2, Thickness = 2.0cm, Vol = 0.3cm^3, Mech Ampl = 1.0, Active Ratio = 10.0

Predictions - Heel Strike

Compute electrical power levels derivable from the boot heel strike.

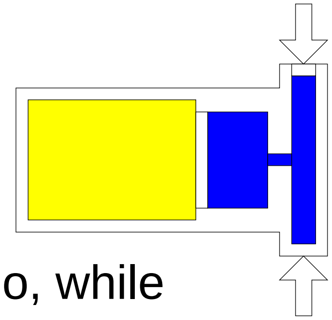
Load environment

- 100 kg soldier walking at 1Hz.
- Output Power

B) Forcing though a 15x stroke amplifier and utilizing larger stack elements

Transducer Thickness: 2 cm

Transducer Area = 2.4cm^2 (1.5cm x 1.5 cm)

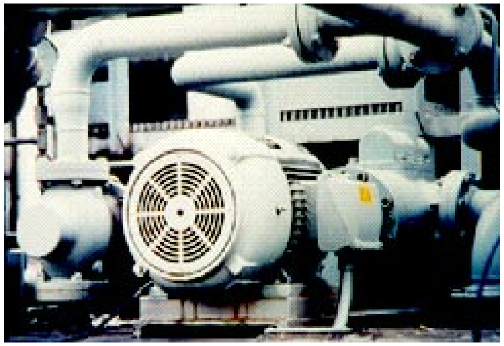


- Note: Mechanical amplifier allows increasing amount of piezo, while maintaining max stress on transducer for best performance

CASE B		PVDF(irad)	PVDF	PZT-4	PZT-5A	PZT-5H	Single Crystal
Deflection	um	287.70	683.00	5.15	5.94	5.63	9.59
Volage Levels (10m)	V	88.15	157.73	7.84	7.76	6.15	12.01
Pasive Power	mW	184	80	34	44	55	396
Active Power	mW	1836	804	340	435	547	3963
Freq = 1Hz, Stress = 31.2MPa, Area = 2.40cm^2, Thickness = 2.0cm, Vol = 4.8cm^3, Mech Ampl = 15.0, Active Ratio = 10.0							

Predictions - Condition Based Maintenance

Compute electrical power levels derivable from vibrating machinery.



Vibration Environment

- 200Hz vibration
- 400 με

Output Power

CASE C		PVDF	PZT-4	PZT-5A	PZT-5H	Single Crystal	AFC
Pasive Power	mW	0.9	498.0	419.5	552.5	359.9	679.4
Freq = 200Hz, Strain = 400ue, Area = 16.0cm^2, Thickness = 0.1cm, Vol = 1.6cm^3, Active Ratio = 25.0							

Load/Requirements:

- as designed: 100 mW for sensor, conditioning, digitize
  500 mW/transmit; 250 mW/receive

Return to Agenda

Next Presentation