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The SERI Wind Energy Program

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ABSTRACT

The SERI Wind Energy Program manages the areas of innovative research, wind systems analysis, and environmental compatibility for the U.S. Department of Energy. Since 1978, SERI wind program staff have conducted in-house aerodynamic and engineering analyses of novel concepts for wind energy conversion and have managed over 20 subcontracts to determine technical feasibility; the most promising of these concepts is the passive blade cyclic pitch control project. In the area of systems analysis, the SERI program has analyzed the impact of intermittent generation on the reliability of electric utility systems using standard utility planning models. SERI has also conducted methodology assessments. Environmental issues related to television interference and acoustic noise from large wind turbines have been addressed. SERI has identified the causes, effects, and potential control of acoustic noise emissions from large wind turbines.

1. INTRODUCTION

Wind energy research at SERI has been conducted in two stages. During the period 1978 - 1981 the Wind Program conducted research and analysis on a wide range of subjects. In addition to generally basic research on innovative concepts and acoustic noise, SERI conducted applied research and analyses on a variety of economic, environmental, legal, and institutional issues associated with wind turbine siting and operation. Also during this period, the SERI program produced analyses of the impact of intermittent generation on the reliability of electric utility systems and developed computer programs for assessing the value of wind systems using standard utility planning models. Finally, the SERI program was responsible for coordinating a variety of DOE-sponsored technical workshops and conferences on wind energy technology.

In 1981 and 1982 the SERI Wind Program significantly refocused its research activities. All work on economic, legal, and institutional issues was either phased out or redirected to other areas. The overall program objective was to conduct high-risk, potentially high-payoff, basic and applied research in areas not being examined by the wind energy industry. Consistent with this new mission, the SERI program is currently conducting or completing research in three principal areas: (1) advanced and innovative wind energy concepts, (2) systems analysis, and (3) acoustic noise.

2. ADVANCED AND INNOVATIVE WIND ENERGY CONCEPTS

The advanced and innovative wind energy concepts program was transferred from DOE to SERI in FY 1978. ERDA initiated the original program to support research and development of innovative wind energy systems. The program goal has been to ascertain the technical and economic viability of innovative concepts for wind energy conversion. R&D efforts have included technical and cost assessments, theoretical and experimental research, and conceptual designs.

Other than necessary in-house technical support, the research conducted in this area has been performed by private companies and universities on a contract basis. These investigations have examined circulation-controlled airfoils, diffuser augmentation, vortex augmentation, electrofluid dynamics (EFD), energy from humid air, dynamic inducers, oscillating vanes, passive cyclic pitch variation with automatic furl control, tethered wind energy systems, and higher-performance airfoils for vertical axis wind turbines (VAWT). Figure 1 shows the principal subcontracts as of FY 1983.

The final phase of R&D in innovative concepts is proof-of-concept prototype testing. Proof-of-concept testing is intended to verify the technical feasibility of promising concepts. Several concepts have shown some promise of technical and economic viability and one, passive cyclic pitch variation, has reached the proof-of-concept phase. Other promising concepts are the diffuser augmented wind turbine (DAWT), the electrofluid dynamic (EFD) wind-driven generator, the dynamic inducer (DI), tethered wind energy systems, and higher performance airfoils for VAWT.

CONTRACT NO.	PROJECT TITLE	SUBCONTRACTOR(S)	PRINCIPAL INVESTIGATOR	ADDRESS
XE-0-9260-1	Innovative Wind Turbine	West Virginia Univ.	Richard E. Walters (304)293-4111	Morgantown, WV 26506
XH-9-8073-1	Diffuser Augmented Wind Turbine (DAWT)	Grumman Aerospace	Ken Foreman (516)575-2221	S. Oyster Bay Road Bethpage, NY 11714
EX-76-C-01-2555	Tornado-Type Wind Energy Systems. Phase II (Tornado)	Grumman Aerospace	Ken Foreman (516)575-2221	S. Oyster Bay Road Bethpage, NY 11714
XH-9-8128-1	Tests & Devices for Wind/Electric Power Charged Aerosol Generators (EFD)	Marks Polarized	Alvin H. Marks (212)767-9600	153-16 Tenth Avenue Whitestone, NY 11357
XE-1-1291-1	Electrofluid Dynamic Wind Generator Program (EFD)	University of Dayton	John E. Minardi (513)229-3845	300 College Park Ave. Dayton, OH 45469
DE--C01 79ET23052	Energy from Humid Air (Humid Air)	South Dakota School of Mines and Technology	Thomas K. Oliver (605)394-2454	Rapid City, SD 57701
E(49-18) 2358	Vortex Augmentors for Wind Energy Conversion (Vortex)	Polytechnic Institute of New York	Pasquale M. Sforza (516)694-5500 X54	Route 110 Farmington, NY 11735
XE-1-1167-1	Optimization of the Dynamic Inducer WES	Aerovironment, Inc.	Graham Gyatt (213)449-4392	145 Vista Avenue Pasadena, CA 91107
XH-9-8035-2	Oscillating Vane Concept	United Tecnnologies Corp.	R.L. Bielawa (203)727-7154	Silver Lane East Hartford, CT 06108
XE-1-1052-1 XE-2-02134-01	Investigation of Passive Blade Cyclic Pitch Variation Using Automatic Yaw Control	Washington University Technology Associates Washington University	K.H. Hohenemser (314)889-6175 or (314)889-6057	2049 Litzsinger Rd. Brentwood, MO 63144 St. Louis, MO 63130
XE-0-9172-2	Tethered WES Assessment	Tetra-Tech, Inc.	Okitsugu Furuya (213)449-6400	630 N. Rosemead Blvd. Pasadena, CA 91107
XE-0-9172-1	Gyroturbine Tethered WES Assessment	Aerospace Systems, Inc.	R. Noll (617)272-7517	121 Middlesex Turnpike Burlington, MA 01803
XE-0-9173-1	Strumming Windmill WEIS Assessment	Payne, Inc.	Peter R. Payne (301)268-6150	1933 Lincoln Dr. Annapolis, MD 21401
XE-0-9173-2	FlexRotor WEIS Assessment	Aerospace Systems, Inc	J. Zvara (617)272-7517	121 Middlesex Turnpike Burlington, MA 01803
AE-1-1045-1	VAWT Airfoil Configurations	Melior Corp.	Paul Migliore (916)756-5522	712 Fifth St. Suite 8 Davis, CA 95616
E-1-1306 P.O.	Testing of the Tethered Gyromill	University of Sydney	Bryan Roberts TWX FishLib AA20056	University of Sydney Dept. of Mechanical Engineering Sydney, NSW 2006 Australia

Figure 1

Principal Subcontractors

FY 1982/83 Innovative Research Projects

2.1 Passive Cyclic Pitch Variation with Automatic Furl Control

The passive cyclic pitch concept has been investigated by Kurt H. Hohenemser of Washington University in St. Louis. The concept incorporates a teetered, two-bladed, horizontal-axis wind turbine (HAWT) with a teeter axis set at a pre-lag angle of about 23° from the blade axis. Teetering the rotor eliminates gyroscopic moments on the tower, and use of the small pre-lag angle, which provides strongly negative pitch-flap coupling, suppresses blade flapping and the associated vibrations and dynamic loads which can occur with rotors conventionally teetered at 90° from the blade axis or hinged in a delta-three configuration.

The passive cyclic pitch concept can provide a number of benefits to HAWT performance and cost. The reduction of rotor vibrations and dynamic loads and the elimination of gyroscopic moments can lower structural requirements and costs for a HAWT. For large turbines, the elimination of gyroscopic moments on the tower by teetering the rotor would permit higher yaw rates and increased energy capture. For small turbines, the suppression of dynamic loads would allow reduction of the number of blades to two, thereby lowering turbine cost. Also, because of the reduced dynamic loads at high yaw angles and yaw rates, the passive cyclic pitch concept can employ rotor furling rather than blade feathering as a means of rotor speed and/or torque control.

Initial research on the passive cyclic pitch concept involved wind-tunnel testing of a small model and the development of computer models analyzing structural loads. This was followed by atmospheric testing of a 7.62-m(25-ft)-diameter prototype near St. Louis. Results of these efforts indicate a significant potential for reduced costs and improved performance relative to conventional HAWTs. At present, an improved 7.62-m(25-ft)-diameter prototype is undergoing proof-of-concept testing at the Rocky Flats Small Wind Systems Test Center in Golden, Colorado.

2.2 The Diffuser Augmented Wind Turbine (DAWT)

Grumman Aerospace Corporation has investigated the DAWT concept since 1975. The objective has been to increase power augmentation effects while lowering diffuser costs by reducing diffuser length. Extensive experimental work, including recent tests in a 1.8 m x 1.8 m (6 ft x 6 ft) open jet wind tunnel at Virginia Polytechnic Institute, has produced power augmentation ratios of 5.5 to 6 over bare turbine performance for diffusers having half-angles of 30°-45°. Combined with cost studies of ferrocement, fiber-reinforced plastic, and aluminum diffusers, these results indicate that the DAWT may be competitive with conventional wind turbines.

2.3 The Electrofluid Dynamic (EFD) Wind-Driven Generator

Research on electrofluid dynamics for wind energy conversion has been performed at the University of Dayton Research Institute since 1976. The EFD concept employs the wind to drive electrically charged aerosols up a potential hill, thereby producing electrical energy from the expended work. Analytical models and wind-tunnel test results have shown potential EFD performance comparable to that of conventional wind turbines. A conceptual design of a full-scale EFD system 65 m (213 ft) high and 400 m (1312 ft) wide has recently been completed at Dayton. For this design SERI has estimated a cost of energy (COE) of ~32 cents/kWh for the first unit and ~22 cents/kWh for the 100th unit. The conceptual design was not optimized for cost; substantial cost reductions may be possible. The design also lacks a yaw capability, thus requiring a site with a highly predominant wind direction. The effects of off-axis winds on EFD performance have yet to be fully analyzed.

2.4 The Dynamic Inducer

The dynamic inducer (DI) tip vane concept, proposed by Van Holten of the Delft Institute of Technology in the Netherlands, has been studied in the U.S. by AeroVironment, Inc. The DI concept uses tip vanes to induce greater mass flow through a turbine, thus augmenting power output. DI research by AeroVironment has included theoretical analyses, wind-tunnel and water-channel testing of small models, and atmospheric tow testing of a 3.5-m(11.5-ft)-diameter model. A peak shaft power augmentation of ~70% was achieved in a wind tunnel at the California Institute of Technology. However, all of the tests have shown the DI to be extremely sensitive to tip vane drag losses. For example, testing in a water channel at the University of Iowa provided a peak power augmentation, based on mass flow measurements, of ~100%, but a peak shaft power augmentation of only ~20% due to tip vane drag losses. In addition, tip vane drag losses severely narrowed the tip speed ratio operating range of each model tested. Thus, the potential of the DI concept for economically competitive wind energy conversion is tied to overcoming the problem of tip vane drag losses.

2.5 Tethered Wind Energy Systems

Tethered, high-altitude wind energy systems have been studied by TetraTech, Inc., Aerospace Systems, Inc., and the University of Sydney in Australia. Research in the United States has been limited to assessment studies, but the work in Australia has reached the experimental stage. Analysis of a hybrid balloon-wing, a vertical takeoff or landing system (VTOL), and a gyromill concept have indicated a potential for cost-competitive wind energy conversion. Recent developments in high-strength, low-weight materials, e.g., kevlar tethers, have greatly enhanced the potential of tethered wind energy systems. Other important factors affecting system potential include deployment restrictions and reliability.

2.6 Higher-Performance Airfoils for VAWT

Research on higher-performance airfoils for VAWT has been performed at West Virginia University (WVU) and Melior Corp. The WVU work has concentrated on circulation-controlled airfoils utilizing air jets near the trailing edges of the airfoils. The Melior Corp. has investigated improved airfoil shapes and the elimination of curvilinear flow effects by conformal mapping of the airfoil section. These latter two concepts may significantly enhance the economic viability of VAWT.

3. SYSTEMS ANALYSIS

3.1 WECS/Utility Value Analysis

Systems analysis for electric utility applications of wind energy conversion systems (WECS) have been conducted in two broad areas: methodology development and applications. Because wind turbines produce power intermittently, they cannot be represented directly in existing utility planning models. SERI produced some of the early analytical work that led to an increased understanding of how intermittent generators impact conventional generating systems [1,2], and developed a package of computer models that can be used for utility planning with WECS. These models simulate the performance of WECS in either a deterministic or probabilistic fashion, and modify the utility's load so that production cost and reliability impacts can be determined. These models are fully documented and publicly available through the National Energy Software Center at Argonne National Laboratory [3]. SERI also conducted an assessment of four different methodologies used for utility planning with WECS [4]. This was a unique study that resolved several issues related to how differences in computer models affect estimates of the value of WECS to electric utilities.

In the area of applications assessments, JBF Scientific and Aerospace Corporation, through subcontracts with SERI, assessed the value of WECS to nine electric utility systems [5]. These utilities are among the best candidates for wind turbines, and this study increased our understanding of the factors that make wind turbines attractive options for utilities.

Finally, SERI is in the process of completing a report that synthesizes all the utility analyses that have been completed to date. This report has two basic objectives: (1) to describe the assessment methodology as it exists today and identify the remaining issues to be resolved, and (2) to normalize and interpret the results from the value analyses that have been completed to date. This report will complement the work that has already been conducted, place it in perspective, and assess what has been learned.

3.2 WECSAM

Arthur D. Little, Inc., developed the Wind Energy Conversion System Analysis Model (WECSAM) to analyze the performance and economics of WECS applications. The final report on WECSAM [6] provides a description of the model and its accompanying data base and includes a discussion of the methods used and information required to run the model. WECSAM is useful for users of WECS and for wind machine manufacturers and designers who are interested in determining the performance and economics of WECS in particular applications.

The performance module reads user-supplied or data-base inputs of the wind turbine power output curve and availability, the annual wind speed (V) and diurnal and monthly variation of V, the power law exponent, and data on the electrical demand at the site. The model then computes an adjusted hourly wind turbine output, compares the output with hourly application demand profiles, computes hourly energy flows, and sums the monthly energy flows transferring the sums to the economic analysis module. The economic analysis module uses the energy flow data plus all the economic/financial inputs to calculate annual life-cycle cash flows, determine cumulative savings, and calculate economic figures of merit (payback period, return on investment, benefit/cost ratio, WECS busbar levelized cost of energy, etc.). The code is available through the National Energy Software Center, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439.

3.3 WESA Studies

SERI has managed two studies that were required by the Wind Energy Systems Act of 1980 (PL 96-345). One study was concerned with federal applications of wind systems while the other was concerned with foreign applications and export potential. Each study resulted in both a DOE report to Congress and a backup SERI report.

The federal applications study determined federal sites at which wind systems are economically competitive with the marginal costs of new conventional energy sources. Data on 9288 possible wind system sites were collected from 16 federal agencies. A preliminary screening was based on generic machines. Savings-to-investment ratios were calculated for each site. The screening indicated that 964 MW of wind capacity at 1452 sites was potentially economically competitive in the near term (1981-1985). Federal agencies nominated 276 sites for a more detailed analysis which used machines selected from a catalogue of representative machines developed for the study. This detailed analysis identified 180 potential sites. Implementation planning guidelines for federal agencies were prepared and brief case studies, following the guidelines, were performed for an Air Force/Navy site at Pinon Peak, California, and a Coast Guard site at Nantucket Island, Massachusetts.

The foreign applications study identified foreign countries in which wind applications appear to be competitive with conventional energy sources and in which barriers to U.S. exports do not appear to be excessive. The study was worldwide in scope and relied almost exclusively on data compiled by other organizations. Data on wind resources, imports, import restrictions, licensing requirements, exchange controls, dependence on energy imports, and balance of payments were gathered for 184 countries and territories. Data on 27 wind applications were also collected, a catalogue of wind machines suitable for export was developed and each application was evaluated with respect to wind speed, projected wind machine cost, and appropriate discount rate.

SERI currently is engaged in a study for the U.S. Air Force/Electronics System Division/North Warning Program of the feasibility of using a wind turbine on a tethered balloon. The study will consider the special design factors associated with a wind turbine mounted on a balloon and will compare system performance to such alternatives as a diesel generator and fuel supply carried on the balloon.

4. ACOUSTICS RESEARCH

4.1 The MOD-1 Turbine Noise Issue

Since the Fall of 1979, SERI (in cooperation with NASA, the General Electric Company, and the Blue Ridge Electric Membership Corporation) has examined acoustic noise associated with the operation of the DOE/NASA MOD-1 wind turbine installed near Boone, North Carolina. A number of sporadic and totally unexpected noise complaints were received from nearby residents during initial testing of the turbine. These early reports were puzzling since complaints were not received each time the turbine operated and attempts to correlate the types of the complaints with the operating mode of the machine proved inconclusive. SERI, with NASA's cooperation, undertook an extensive study for DOE to establish and document the physical mechanisms responsible for the noise, the propagation paths of noise to the affected homes, the nature of the annoyance impact on humans, and techniques to eliminate the adverse effects or at least reduce them to imperceptible levels.

4.2 Investigative Procedure

A definitive set of physical measurements documenting the characteristics of the MOD-1 acoustic emissions, the structure of the intervening atmosphere between the turbine and the affected homes, and the external and internal acoustic responses of two of the homes was acquired through a series of on-site studies. To further our understanding of the actual physical processes involved, a number of supporting experiments have been performed using the NASA MOD-0 experimental turbine at Plumbrook, Ohio, a small wind turbine at the Rocky Flats Wind Energy Test Center in Colorado, and wind-tunnel facilities of MIT and the University of Colorado. In addition to the in-house SERI work, MIT Fluid Dynamics Laboratory provided aeroacoustic modeling and Pennsylvania State University, Pacific Northwest Labs, and the University of Virginia furnished needed atmospheric data and developed an understanding of the propagation paths involved.

4.3 Conclusions Reached

The noise source. Our analysis of the actual MOD-1 field data and the results of the wind-tunnel and small wind turbine tests confirmed that rapid transient lift fluctuations in the turbine blade airloads as they passed through the tower leg wakes were ultimately responsible for the annoyance. In particular, the leg wakes influenced the severity of these lift transients by (1) their provision of a spatial coherency parallel to the major axes of the cylindrical-shaped tower legs and the spanwise direction of the rotor blades in the form of shed vortex tube structures, (2) their lateral dimensions, and (3) their time-varying (dynamic) properties as opposed to mean quantities. The analysis also showed the severity of the impulses generated was not a unique function of the leg wake momentum deficit and that other factors were involved. The unsteady aerodynamic process initiated as the blades pass through the wakes includes the transient loss of lift through varying degrees of leading edge separation and dynamic stall, which have been shown to be related to wake turbulent structural properties and the airfoil shape of the blades themselves.

The propagation mechanism. An analysis of the propagation of the MOD-1 noise by Pennsylvania State University revealed that surface and ground propagation were negligible in comparison with terrain reflection and atmospheric refraction. Strong focusing of the emitted acoustic impulses was responsible for local, far-field enhancements in excess of 25 dB or more.

The nature of the human annoyance. Our analysis of the effect of the low-frequency, energy-dominated acoustic impulses on two of the frequently affected homes revealed that these buildings were undergoing elastic deformation under the influence of the MOD-1 excitation. The excitation of lightly damped structural modes by these periodic acoustic loadings caused cavity (Helmholtz) and air volume resonances within the rooms of the homes; these resonances in turn caused loose objects to rattle. Of major importance, we hypothesize, are the strongly oscillatory, low-frequency pressure fields created within the smaller rooms of the homes and what we believe to be a dynamic coupling of this harmonic energy to human body resonances creating the sensation of whole-body vibration and internally generated "sound." A measurement of the indoor threshold perception of the MOD-1 impulses at one of the two homes compared to documented cases of human annoyance which have been attributed to low-frequency noise has led us to suggest a series of emission level limits for operating wind turbines. These suggested limits (measured 1.5 rotor diameters upwind or downwind of the turbine) are specified in terms of absolute (linear-weighted) band pressure levels of 60, 55, 45, and 45 dB in the respective 8, 16, 31.5, and 63 Hz standard (ISO) octave frequency bands.

Methods for impulsive noise abatement. Several avenues for amelioration of the MOD-1 impulsive noise were investigated since it became clear that control at the source was the only practical approach. SERI has recommended the installation of helical strake or spiral fence aerodynamic spoiling devices on the large cylindrical legs of the MOD-1 tower in order to destroy the highly organized, two-dimensional wake vortex circulations and in so doing reduce the strong, impulsive emissions to levels below human perception an acceptable percentage of the time.

4.4 Continuing SERI WECS Noise Reduction and Source Characterization Research

SERI WECS aeroacoustics research has expanded beyond the specifics of the MOD-1 situation to the characterization of the acoustic emissions from various generic wind turbine designs, including the upwind horizontal- and vertical-axis (Darrieus) turbines. Comparisons have been made using the DOE/NASA MOD-2 horizontal-axis and DOE/SNLA and NRC/IREQ/DAF vertical-axis (Darrieus) turbines. The role of the atmospheric turbulent structure and its diurnal variation as the inflow of a large wind turbine has been recognized as a source in controlling the observed unsteadiness in the blade airloads and the accompanying levels of coherent, low-frequency noise radiation. Research related to the MOD-1 situation has been used to develop a more comprehensive understanding of the impact of the various turbine design parameters, such as airfoil shape, rotation speed, etc. (both individually and collectively), on the radiated levels of potentially annoying, low-frequency sound. Several specialized instrumentation and data analysis techniques have been developed by SERI for the evaluation of acoustic emissions of large wind turbines. At least one of these techniques may allow objective evaluation of the level of unsteadiness in blade airloads by interpretation of the spectral characteristics of the radiated acoustic pressure field.

5. REFERENCES

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