Performance and Feasibility Analysis of a Wind Turbine Power System for Use on Mars

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ABSTRACT

A wind turbine power system for future missions to the Martian surface was studied for performance and feasibility. A C++ program was developed from existing FORTRAN code to analyze the power capabilities of wind turbines under different environments and design philosophies. Power output, efficiency, torque, thrust, and other performance criteria could be computed given design geometries, atmospheric conditions, and airfoil behavior. After reviewing performance of such a wind turbine, a conceptual system design was modeled to evaluate feasibility. More analysis code was developed to study and optimize the overall structural design. Findings of this preliminary study show that turbine power output on Mars could be as high as several hundred kilowatts. The optimized conceptual design examined here would have a power output of 104 kW, total mass of 1910 kg, and specific power of 54.6 W/kg.

INTRODUCTION

Future missions to Mars will require power generation capabilities far beyond those of conventional space power systems. To sustain life and equipment for extended periods will require very large energy stores. To synthesize propellant on Mars for the return trip will require even more power. Currently, the two main proposals for energy generation during planetary exploration are solar power and nuclear power. Research has shown that these methods are feasible, but each has major drawbacks that require serious consideration. Solar power methods are grossly inefficient, cumbersome, and heavy. Nuclear power methods require elaborate safety systems and violate international agreements on the launch of radioactive materials.

Wind power might provide an alternative to these two power systems. Mars contains a thin atmosphere possessing high wind speeds. Wind turbines have proven feasible on Earth after years of research and development. Performance, structural dynamics, and design philosophy of wind turbines are well understood. Due to their success and relative simplicity, wind turbines might provide a good method for power generation on Mars.

An ideal power system would provide a high level of power at a minimum weight. This is because the costs associated with transport of such a system to Mars are extraordinarily high and are a direct function of total mass. Construction costs of the system would be small compared to the transportation costs. Thus, the ratio of power output to total mass (known as specific power) is the major design concern for such a system. It is therefore essential to predict both the power output and the total mass when studying the feasibility of a power system for Mars.

Because of this, computer code was developed to analyze power capabilities of conceptual wind turbines. This code was used to determine power levels, efficiencies, thrust loading, and other critical design parameters of the turbine, given inputs such as blade shape, atmospheric properties, airfoil characteristics, blade shape, and general turbine geometry.

Next, a structural design was developed for the wind turbine system. After careful review, it was determined that conventional Earth-based structural designs would be inappropriate for the environment of Mars. These designs would be very heavy, difficult to install, and incapable of providing sufficient height for the turbine. Instead, a new design was developed that would be much lighter, easier to install, and capable of providing the necessary altitude for the turbine. This system would utilize a helium balloon and tether to raise the turbine to an appropriate height.

In order to study feasibility of this system, more computer code was developed and utilized to model its overall structural characteristics. With this code, it was possible to analyze total system mass, static loading, and other important design parameters. With the system analysis code, performance curves could be generated by changing design variables. After plotting specific power as a function of several design variables, it was then possible to locate the design configuration that would yield the highest specific power. With this information, an optimal design could be selected and examined further for feasibility.

TURBINE PERFORMANCE ANALYSIS

The program used to analyze wind turbine performance on Mars was developed from existing code. The existing code was written in FORTRAN by Dr. Robert E. Wilson and Stel N. Walker of Oregon State University in 1975 [1]. This code was used to evaluate performance of Earth-based wind turbines. In 1981, it was modified by Dr. Larry A. Viterna of NASA Lewis Research Center to incorporate additional features and increase accuracy.

This code was then converted to C programming language using FORTRAN to C translation software [2]. A graphical user interface was designed to simplify use of the program. Editing and compiling was performed through the software *VisualAge for C++ for Windows* by IBM. For more information regarding the design and refinement of this code, see [3].

The program could compute power output, efficiency, torque, and axial thrust loads. Atmospheric inputs included wind speed, density, and viscosity. Blade geometry inputs included twist and chord length along the blade, and total blade length. Airfoil properties were given through a table of lift and drag coefficients versus angle of attack. Other inputs included rotor speed, number of blades, and hub radius.

The new code contained many improvements over the original. First, the code was expanded to accurately model turbine behavior for the atmosphere of Mars. The original code used only the atmospheric properties of Earth and could not account for the very different atmosphere that exists on Mars. New algorithms were added to model behavior for any given air density and viscosity. Second, the subroutines involving the airfoil characteristics of the turbine blades were rewritten to accommodate a wider variety of airfoil types. The original code used only NACA 0012, 4418, and 23018 airfoils. These airfoils do not perform well on Mars due to the extremely low Reynolds numbers encountered there. High turbine performance on Mars requires good low-Reynolds-number airfoils and thus the new code needed to accommodate these new types of airfoils. The new code allows the input of airfoil characteristics through a table relating lift and drag coefficients versus angle of attack. Third, additional coding was added to model airfoil behavior beyond stall. The Viterna-Corrigan post-stall model [4] was incorporated to determine lift and drag coefficients when the blades stall. This coding provided better modeling accuracy. Fourth, the code was clarified and condensed. The original code contained many inefficient algorithms, unnecessary variables, and poor comments. These were all amended to reduce computation time and enhance readability.

TURBINE PERFORMANCE RESULTS

Once the analysis code was developed, it was used to study power capabilities of wind turbines in the Martian environment. It was quickly realized that airfoils that perform well on Earth do not perform well on Mars. Due to the very low atmospheric density on Mars, the Reynolds number related to the turbine blades is extremely low (on the order of 10^4). Conventional turbine airfoils experience too much drag in this regime, which significantly reduces efficiency. Therefore, unconventional airfoils would be needed to provide good turbine performance on Mars.

After reviewing twenty-six different airfoils designed for the low-Reynolds-number regime [5], it was concluded that good turbine performance would be possible on Mars. Best performance came from the GM 15, SD 7037A, SD 8000, and BE 50 airfoils. Efficiencies of at least 40 percent and power levels on the order of hundreds of kilowatts could be attained, given proper airfoil selection and blade design. This is close to performance levels attained on Earth and is good enough to warrant further examination of wind turbine systems.

CONCEPTUAL SYSTEM DESIGN

After concluding that significant power levels and efficiencies could be realized on Mars, it became necessary to study the overall wind turbine system. The wind turbine, generator, housing, and structural support needed to be integrated into one design. Once a design was decided upon, it would then be possible to analyze total system mass and power capability in order to assess feasibility.

To begin, power output of a wind turbine system is given by the equation

$$P = \tfrac{1}{2}\eta\rho AV^3 \qquad (1)$$

where P is power, η is turbine efficiency (found using the performance analysis code), ρ is air density, A is swept frontal area of turbine, and V is wind speed. Through Eq. 1, it can be seen that wind speed has the greatest influence on power output.

The atmosphere of Mars is very different from that on Earth. The pressure and density of Mars's atmosphere is about one percent that of Earth's atmosphere. However, wind speeds can be up to five times faster on Mars than on Earth. These two phenomena counteract each other when affecting power output, as can be seen by Eq. 1. The net effect is that power output on Mars is roughly comparable to that on Earth.
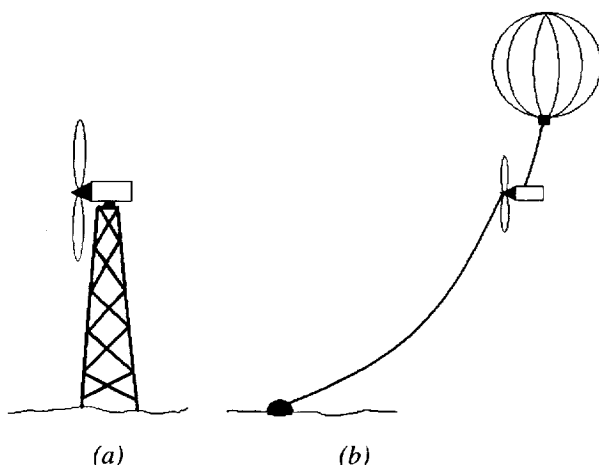
Figure 1: Possible wind turbine system designs. (a) Conventional tower structure. (b) Balloon and tether system. Conventional tower structures might not be feasible on Mars.

Unfortunately, wind speeds capable of providing this high level of energy exist only at around 7 to 10 km altitude in the Martian atmosphere [6]. Conventional Earth-based wind turbine systems consist of a turbine and generator affixed to the top of a large tower (Fig. 1a). On Mars, this design would not be practical for several reasons. First, in order to achieve significant altitude, the tower would have to be large and thus extremely heavy. Second, installation of such a design on the Martian surface would be incredibly difficult due to the complexity of struts, foundations, and assembly procedures. Third, it would be impossible to create a tower strong enough to hold the turbine at such a high altitude, even in the reduced gravity of Mars.

A totally new system structure would need to be developed if the wind turbine concept were to work. In response to this, a conceptual system was developed in which a helium-filled balloon would be used to suspend the turbine at high altitude (Fig. 1b). The very large balloon would be connected to the turbine assembly with cables and/or struts. The system would be anchored to the ground using a very long tether. A lightweight electrical cable following the tether would transmit power down to a ground station for conditioning and distribution.

SYSTEM OPTIMIZATION METHODS

This design can be optimized based on two independent variables: turbine altitude and blade length. Power output, tether length and diameter, generator size, transmission cable diameter, and balloon diameter are all functions of these two independent variables.

The optimal design is not obvious upon simple inspection. Many phenomena counteract each other to affect power output. At higher altitudes, wind speed increases, but atmospheric density decreases. It is not immediately clear which of these factors has more effect. Closer investigation of atmospheric data reveals that increasing altitude will actually increase power output for a given turbine size.

However, total power output is not the real measure of feasibility. The real measure is specific power, the ratio of power output to total system mass. For example, if design A produces twice the power of design B, but weighs ten times as much, then design A is not the best design. In this case, it would be more efficient to use two of B instead of one A. Using two systems of design B would achieve the same total power capabilities of design A for only one-fifth the weight.

Therefore, in order to optimize the design for feasibility, total system mass must be computed in addition to power output capability. This is not a simple task. When turbine altitude increases, total mass increases rapidly. This is because to reach higher altitudes, a longer tether is needed. Since the tether was found to constitute more than half the system mass, this phenomenon is critical. When the tether gets longer, it weighs more and thus must be larger in diameter to support its own weight. Increasing its diameter increases its weight further. A heavier tether also increases the size requirement for the balloon. In addition, a larger balloon is required at higher altitudes because buoyancy decreases as atmospheric density drops. As balloon size grows, the wind drag it experiences also grows. This increases the tension in the tether, and again the tether must increase in diameter. Balloon and tether sizes are coupled in such a way that a small increase in altitude will dramatically influence total system mass.

It is unclear upon inspection which altitude will provide the best specific power. Increasing altitude increases both power output and total mass. It is also unclear which turbine blade length will provide the best specific power. When blade length increases, power output and turbine mass both increase. These two parameters increase at different rates and it is not obvious which blade length will provide optimal results.

Since the ultimate measure of design feasibility is specific power, it was necessary to generate performance curves of specific power versus altitude and blade length. With these curves, it would be possible to locate the altitude and the blade length that would provide maximum specific power. Once these two parameters are chosen, the rest of the system parameters can be determined and the system is then well understood.

SYSTEM ANALYSIS

In order to generate performance curves, a computer code needed to be developed to quickly compute power output, system mass, and specific power for any given turbine altitude, blade length, and material construction. This code was written in C++ and a graphical user interface was created for ease of use. For more information regarding the specifics of this code, see [3].

The analysis code was developed based on many design assumptions and approximations. Only static loads were applied to the system; fatigue failure was not examined in the code. The tether connecting the system to the ground was assumed to sag under its own weight and follow the shape of a catenary curve. Electrical cables ran along the tether. Slope of the tether at the ground anchor was designed at zero degrees so that tether force on the anchor would be purely horizontal. A single 200-m cable provided the connection between balloon and turbine. Drag from the balloon, cables, and turbine assembly was accounted for in the model. The atmosphere and helium were approximated as ideal gases to simplify the calculation of balloon buoyancy. Turbine blade mass for any given blade length was computed by extrapolating from actual wind turbine data. Likewise, generator and electrical cable masses for any given power level were computed from curve-fits of actual aircraft generator data [10] and electrical cable data [12].

Once turbine altitude, blade length, turbine efficiency, factors of safety, atmospheric properties, and structural material properties are given, the code can then compute the rest of the system parameters. Power output is computed using turbine efficiency, blade length, and atmospheric properties. Transmission cable diameter and generator size can be computed from this power requirement. Their masses can then be computed from their sizes. Turbine mass is calculated from the blade length, as discussed above. Since balloon diameter and tether dimensions are coupled parameters, an iterative process is used to find a solution that satisfies both the tether and balloon size requirements simultaneously. From these sizes, the tether, balloon, and helium masses can be found. Total system mass is then found by summing all the component masses. Specific power is then simply the power output divided by the total system mass.

Once the code was built, it was then possible to generate performance curves by varying materials, altitude, and turbine size (Fig. 2). With these performance curves, the optimal design configuration (that which achieves the highest specific power) could be determined by locating the peak of the performance
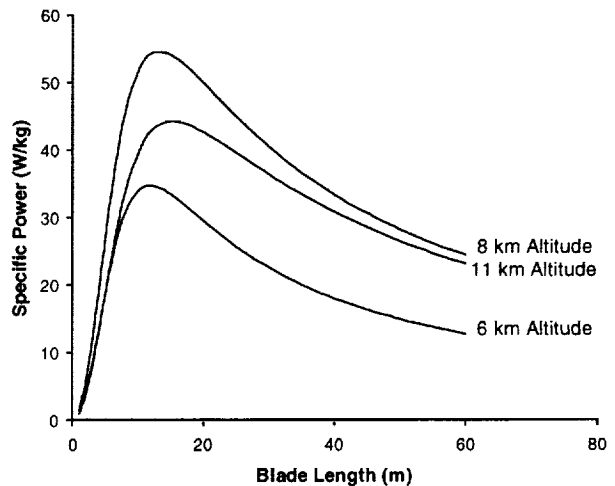

Figure 2: *Specific Power vs. Blade Length for Various Turbine Altitudes (Aramid Fiber Tether). The optimal design has 8 km turbine altitude, 13 m blade length. Note that the highest altitude does not provide the best specific power.*

curve. In Fig. 2, this optimal configuration is represented by the tallest peak on the graph; the optimal design would have a blade length of 13 m and a turbine altitude of 8 km. Performance curves for systems that use other tether materials are similar in shape to the one shown here.

SYSTEM OPTIMIZATION RESULTS

The optimal design configurations for various tether materials is shown in Table 1. The atmosphere and material property data used in the analysis are shown in Tables 2 and 3, respectively. The optimal turbine altitude for all tether materials was 8 km. Optimal blade length, however, was different for each tether material.

The optimal design of all these would consist of an Aramid fiber tether and two aluminum electrical cables each 58 km in length, a plastic film helium balloon 80 m in diameter, a 100-kW aircraft-grade generator, and two lightweight turbine blades of length 13 m. The optimized design would operate at an altitude of 8 km, would have a launch mass of about 1910 kg, and would have a specific power around 55 W/kg.

These parameters were based on a turbine efficiency of 43 percent, balloon film mass of 10 grams/m^2, balloon drag coefficient of 0.2, and tether factor of safety of 2.0 based on ultimate strength. Turbine efficiency of 43 percent was found to be an attainable value from the power capability analysis described earlier. Balloon film mass was based on the estimated weights of films such as Mylar or biaxial nylon-6. Balloon drag coefficient was found using a

Table 1: Optimized Designs for Various Tether Materials.

Tether Material	Blade Length m	Power Output kW	Total Mass kg	Specific Power W/kg
Steel	34	712	35 800	19.9
Aluminum Alloy	36	799	43 900	18.2
Titanium Alloy	35	755	40 400	18.7
E-glass Fiber	16	158	3 510	45.0
Carbon Fiber	15	139	2 940	47.1
Aramid Fiber	13	104	1 910	54.6

Table 2: Atmosphere Data for Mars.

Altitude km	Density kg/m^3	Wind Speed m/s
1	0.01270	3
2	0.01170	6
3	0.01080	12
4	0.01000	19
5	0.00930	25
6	0.00857	33
7	0.00785	41
8	0.00730	50
9	0.00670	58
10	0.00620	66
11	0.00570	72
12	0.00525	78
13	0.00485	84
14	0.00442	90
15	0.00405	96
16	0.00371	100
17	0.00340	104
18	0.00310	108
19	0.00280	112
20	0.00257	115

Sources: [6], [7]

Table 3: Property Data for Tether Materials.

Tether Material	Density kg/m^3	Tensile Strength GPa
Steel AISI 4142 Q&T	7800	1.93
Aluminum Alloy 7075-T6	2710	0.593
Titanium Alloy 6Al-4V	4850	1.10
E-glass Fiber	2580	3.45
Carbon Fiber	2150	3.30
Aramid Fiber Kevlar 49	1440	3.60

Sources: [8], [9]

A special airfoil would need to be designed to perform well at the low Reynolds numbers experienced on Mars. This airfoil would need high lift-to-drag ratios in order to increase turbine efficiency. Design would probably be similar to those discussed in [5].

An autonomous balloon pressure regulator would need to be designed. The atmospheric pressure on Mars fluctuates greatly on a daily and yearly basis due to changes in temperature. Such a regulation system would need to bleed off or absorb balloon pressure when atmospheric pressure drops during the night and the winter. This aspect of a wind turbine system has not been examined yet.

Lightweight composite construction throughout the system would be essential. The turbine blades are the strongest candidates for this type of construction, because they account for a significant portion of the total mass. Minimal weight is important not only because it reduces transportation costs, but also because it is a self-influencing parameter. That is, to shave 50 kg off the turbine blades might actually shave 400 kg off the entire system due to tether and balloon size reductions.

chart of drag coefficient versus Reynolds number for a sphere [10]. The tether factor of safety was based on recommendations from a technical article concerning an Earth-based balloon and tether system similar to that analyzed [11].

DISCUSSION

From this preliminary analysis, the ground tether was determined to be the primary design driver. More than half of the system weight comes from this single component. It is critical that the materials used in the tether have a very high strength-to-weight ratio. At about 8 to 10 km turbine altitude, the higher power levels attained by increasing altitude are not enough to offset the tether weight penalty.

A lightweight generator would have to be designed. As said about the turbine blades, every effort to reduce component weight must be taken. This generator might need to be designed for variable speed operation, depending on the specifics of the turbine design.

Dynamic loading, cyclic loading, creep, and stability would need to be studied further. The analysis performed here examined only static loading with regards to ultimate tensile strength. Due to sparse wind data, it was not possible to study cyclic loading, fatigue, or creep in the system. In addition, this analysis did not examine the stability of this particular system design. It is highly likely that a system would require more support between balloon and turbine than that provided in this simple preliminary design.

Temperature and ultraviolet radiation effects on construction materials would need to be studied. Atmospheric temperatures vary from roughly -100 to -50 degrees Celsius [6]. Ultraviolet irradiation is orders of magnitude higher on Mars than on Earth. This would strongly affect materials selection. Epoxies used in composite rotor blades, for example, might break down under UV radiation or fatigue quickly at low temperature. Because this was only a preliminary feasibility study, this environmental aspect of the design was not examined in great depth.

A detailed, long-term survey of wind speeds at many altitudes for many locations would be necessary. Present knowledge of the Martian atmosphere is not detailed enough for realistic wind turbine planning. The wind speed data used in this analysis were taken from measurements made by Mariner 9 [6]. Peak wind speeds were measured at 45 degrees north latitude. However, some data suggest that wind speeds drop by 75 percent at a latitudinal deviation of only 5 degrees. It appears that only a narrow region of the Martian atmosphere contains high-energy winds. Unfortunately, this narrow region might not be the most suitable for habitation or exploration. In addition, this Martian jet stream probably moves with time, much the way Earth's jet stream does. This would make long-range planning for such a wind turbine system extremely difficult. More atmospheric research would be needed before any final plans for wind turbine systems could be made.

Further research into balloon design might prove beneficial. The balloon shape studied here was spherical (Fig. 3a). The shape of the balloon might be modified to provide lift, as in a wing (Fig. 3b), or to provide enhanced flow for the turbine, as in a duct (Fig. 3c). With a duct design, the turbine might be located within the balloon, and the duct would provide greater effective
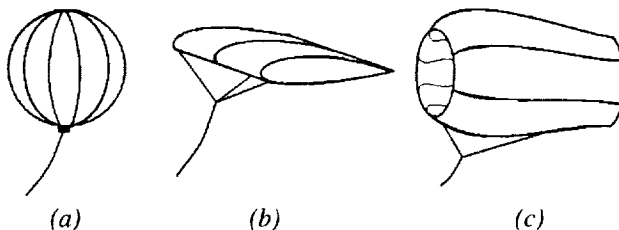

Figure 3: Possible balloon designs. (a) Sphere. (b) Wing. (c) Duct. A wing would increase the lift-to-drag ratio on the balloon, while a duct might enhance the effective wind speed for a turbine situated within.

wind speeds. It is not immediately clear whether these ideas would enhance performance and feasibility.

CONCLUSIONS

A preliminary performance and feasibility analysis was conducted for a conceptual wind turbine power system for use on Mars. Two different computer codes were developed to aid in this study. The first code analyzed the aerodynamic details of the turbine itself to determine power output, efficiency, torque, and loads. This code was used to determine realistic, attainable power levels and efficiencies. After finding these, it was concluded that further research was justified. At this point, the second code was developed to analyze the structural details of the entire system, which included balloon, tether, turbine, generator, housing, and electrical cables. The second code was used to generate performance curves for the overall system. With these curves, it was possible to locate the optimum design configuration.

Wind turbines would not be effective at low altitudes (below 1 km). Wind speeds and atmospheric densities there are too low to provide significant power levels. High altitudes might be reached by using a balloon and tether system to lift the turbine high into the Martian jet stream. If this design were used, the primary design driver would be the tether. It would account for more than half the system weight and would influence size requirements for other components.

The initial results of these preliminary analyses show that the optimum design would utilize an Aramid fiber tether. The blades would be 13 m long and the turbine would be suspended at an altitude of 8 km. As a result, the balloon would be 80 m in diameter, the tether and electrical cables would be 58 m long, the system mass would be 1910 kg, the power output would be 104 kW, and the specific power would be 54.6 W/kg. A diagram of the system is shown in Fig. 4.
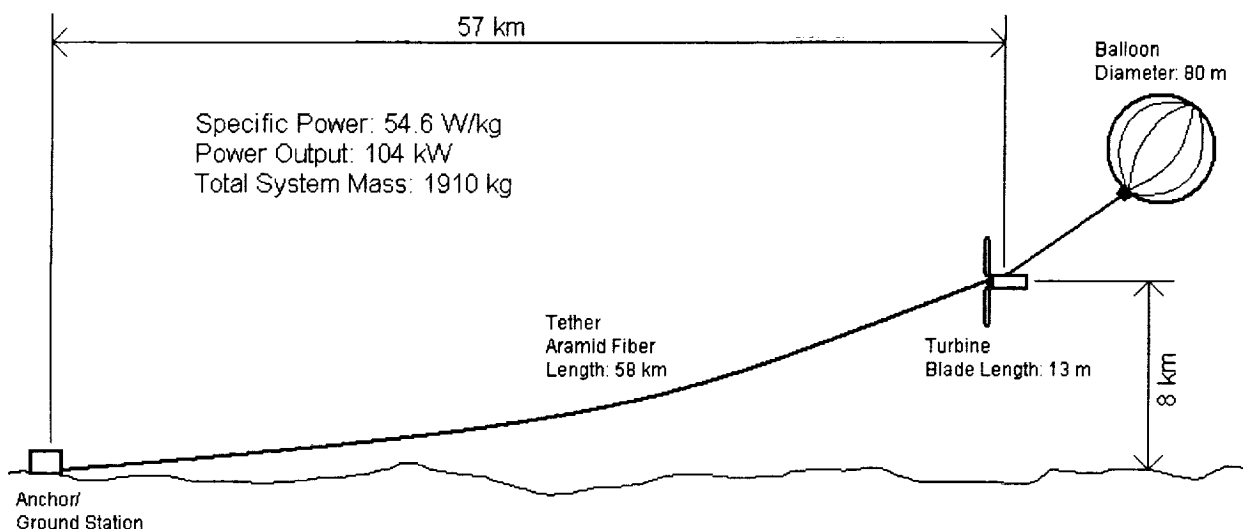
Figure 4: Optimized conceptual design. Drag on the balloon and turbine pushes the system far downwind.

Much more research would need to be conducted to take the wind turbine concept beyond this preliminary conceptual design. Detailed wind surveys, material degradation analyses, airfoil/balloon/generator design, and tether studies would need to be performed if this concept were to be taken beyond this preliminary design stage.

REFERENCES

1. Wilson, Robert E., and Stel N. Walker, 1975: *A FORTRAN Program for the Determination of Performance, Loads, and Stability Derivatives of Wind Turbines*, Corvallis, Oregon: Oregon State University.

2. AT&T Bell Laboratories and Bellcore, 1997: *FORTRAN to C Conversion Utility*, ftp://netlib.bell-labs.com/ netlib/f2c/ libf2c.zip.

3. Lichter, Matthew D., 1997: *A Program for the Analysis of Extraterrestrial Wind Turbines*, unpublished document, Cleveland, Ohio: NASA Lewis Research Center.

4. Lissaman, Peter B. S., 1994: "Wind Turbine Airfoils and Rotor Wakes," *Wind Turbine Technology*, D. Spera, ed., New York: The American Society of Mechanical Engineers, pp. 288-289.

5. Selig, Michael S., John F. Donovan, and David B. Fraser, 1989: *Airfoils at Low Speeds*, Virginia Beach, Virginia: H. A. Stokely.

6. Kaplan, David, 1988: *Environment of Mars*, NASA TM-100470, Houston, Texas: Lyndon B. Johnson Space Center.

7. Marov, M. Ya., V. V. Kerzhanovich, V. S. Avduevsky, and M. K. Rozhdestvensky, 1976: "Measurements With the Mars 6 Lander and a Model of the Martian Atmosphere," *Space Research*, Vol. XVI, M. J. Rycroft, ed., Berlin: Akademie-Verlag, p. 1026.

8. Callister, William D., 1997: *Materials Science and Engineering: An Introduction*, New York: John Wiley and Sons.

9. Shigley, Joseph Edward, and Charles R. Mischke, 1989: *Mechanical Engineering Design*, Fifth Edition, New York: McGraw-Hill.

10. Baumeister, Theodore, ed., 1978: *Marks' Standard Handbook for Mechanical Engineers*, Eighth Edition, New York: McGraw-Hill, pp. 2-38, 3-35, 4-50, 6-11, 6-60, 8-90, 11-69, 15-60, 15-66.

11. Redkar, R. T., 1977: "Scientific Ballooning in India," *Space Research*, Vol. XVII, M. J. Rycroft, ed., Oxford: Pergamon Press, pp. 779-793.

12. Fink, Donald G., ed., 1978: *Standard Handbook for Electrical Engineers*, Eleventh Edition, New York: McGraw-Hill, p. 23-11.

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