Mathematical Model of Underwater Simulation of Astronaut Extravehicular Activities

Y. C. PAO*
University of Nebraska, Lincoln, Nebr.

Theme

A SCALING equation is presented for predicting the metabolic rate of astronauts performing extravehicular activities in weightless conditions by underwater simulation. To determine the additional energy consumed during underwater maneuvering, a mathematical model representing the suited subject and composed of simple geometric shapes, has been constructed so that the integral equations of drag can be expressed in terms of motion vectors at the joints of the body. Also discussed are the limitations and feasibility of the proposed method, computer programs for executing the entire scaling analysis, and recommendations for a Data Acquisition System and experiments for determining the drag coefficients.

Content

Various simulation techniques have been considered for the study of pressure-suited astronauts performing extravehicular maintenance and assembly functions in weightless conditions. Of these, water immersion offers the greatest promise because it permits a neutrally balanced state approaching the free fall condition to be achieved for extended periods of time. However, the water immersion technique is not without weaknesses. The viscous nature of water as a suspension medium detracts from simulation fidelity as rates of rotation, translation and body movements associated with work exceed 2–3 fps. A scaling equation is therefore needed to define the relationship between astronaut tasks performed under weightless conditions and identical tasks under neutrally buoyant conditions simulating the real world.

The scaling analysis involves the calculation of the additional energy expenditure during underwater maneuvering for overcoming drag which is assumed to be the main difference between the underwater and the actual weightless space environment. Because of the restraints imposed by the pressure suit and the concern for mission safety, extravehicular activities are performed at low speed. A detailed analysis of the drag problem has led to the conclusion that it is the principal factor detracting from water immersion as a high-fidelity simulation technique.

To predict the metabolic rates E_{MS} of astronauts performing space tasks by simulation, the physiological data and the motion histories of the underwater maneuvering subjects should be recorded. It will be left to the life scientists to decide on what type of physiological data they want to record and work out the metabolic rates E_{MW} for doing the same tasks under water. The scaling equation for determining E_{MS} is

$$E_{MS} = E_{MW} = E_D$$

where E_D is the additional energy consumed due to drag.

Received June 28, 1971; presented as Paper 71-852 at the AIAA/ASMA Weightlessness and Artificial Gravity Meeting, Williamsburg, Va.; August 9–11, 1971; synoptic received September 8, 1971; revision received December 16, 1971. Full paper is available from AIAA, Price: AIAA members $1.50; nonmembers, $2.00. Microfiche, $1.00. **Order must be acccompanied by remittance.**

Index categories: Computer Technology and Computer Simulation Techniques; Crew Training; Hydrodynamics.

* Professor of Mechanical Engineering and of Engineering Mechanics. Member AIAA.

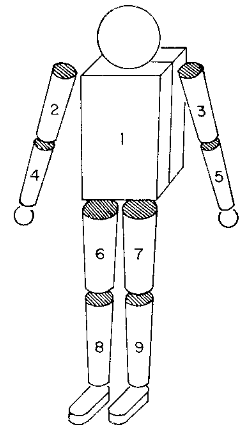

Fig. 1 Mathematical model.

In order to evaluate the drag energy E_D, the mathematical model shown in Fig. 1 has been used in the analysis. The segments are assumed to be rigid, homogeneous bodies of simple geometric shape, and hinged at fixed pivot points to resemble the human body. By attaching accelerometers at the joints of the body segments as shown in Fig. 2, the motion histories of the subjects can be easily recorded.

A typical segment of the body is shown in Fig. 3 with the velocity and position vectors shown at its end joints. The drag energy can then be expressed in terms of these vectors as

$$E_D = \frac{\rho}{2} \sum_{k=1}^{\infty} \frac{1}{L_k} \int_0^{t_d} C_D(t) \int_0^{L_k} W_k(x)(A_k x^2 + B_k x + C_k)(a_k x^2 + b_k x + c_k)^{1/2}\, dx\, dt$$

where L_k's are the length of the segments, ρ is the density of water, t_d is the duration of a planned task, and

$$a = (1/L^2)|(\mathbf{V}_A - \mathbf{V}_B) \times (\mathbf{X}_B - \mathbf{X}_A|^2$$
$$b = (2/L)[\mathbf{V}_A \times (\mathbf{X}_B - \mathbf{X}_A)] \cdot [(\mathbf{V}_B - \mathbf{V}_A) \times (\mathbf{X}_B - \mathbf{X}_A)]$$
$$c = |\mathbf{V}_A \times (\mathbf{X}_B - \mathbf{X}_A)|^2; \ A = (1/L^2)|\mathbf{V}_A - \mathbf{V}_B)|^2$$
$$B = (2/L)\mathbf{V}_A \cdot (\mathbf{V}_B - \mathbf{V}_A); \ C = |\mathbf{V}_A|^2$$

In these expressions, the symbols $\times$ and $\cdot$ stand for cross and dot products of vectors, respectively. Computer programs have been written to evaluate the integral equation E_D using recorded motion histories of the body joints as input.

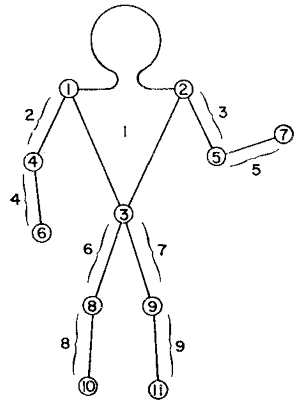

Fig. 2 Positions for Attachment of accelerometers measuring motion in three perpendicular directions.

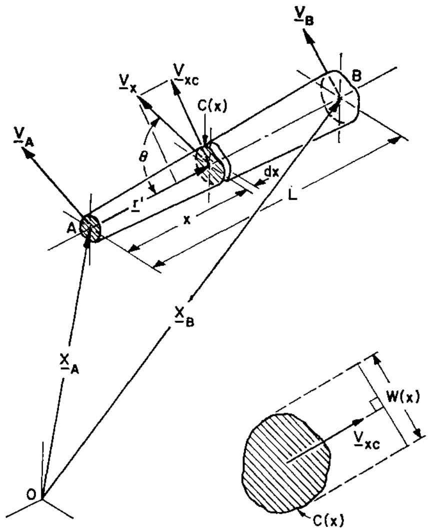

Fig. 3 Velocity and cross-sections along the axis of a typical body segment.

Table 1 Comparison of drag Area,[a] $A_D = C_DA = D/q$, ft²

Body position	Water-immersion simulation	Aircraft trajectory simulation	Schmitt's Investigation
Standing	8.7	9	9
Crouch	2.4	2.4	2 to 3
Prone	1.2	1.15	1.2

[a] In arriving at the results, the densities of water (1.94 lb-sec²/ft⁴) and for air at 10,000 ft (0.00176 lb-sec²/ft⁴) have been assumed.

Table 2 Average drag area[a] of clothed subjects, A_D, ft²

Body position	Yaw angle, ψ	A_D
Standing	0°	8.70
Sitting	0°	5.74
Supine	180°	0.962

[a] Because of the suit constraints, it is unlikely that either of the two squat positions of Schmitt's investigation can be achieved.

Based on the available information[1,2] regarding drag coefficients for human body, some calculated results of drag areas are presented in Tables 1 and 2. When the velocity of motion is below 2 fps, it is found that the drag coefficient C_D of a human body immersed in water is between 1.0 and 1.3. For producing reliable scaling results, more extensive drag tests are recommended. Experiments pertinent to the scheduled movements of underwater tasks should be conducted to determine the drag coefficients of basic constituent attitudes moving at various velocities. These results would enhance interpolation of the other attitudes needed for the scaling analysis.

Also recommended is a Data Acquisition System[3] capable of generating motion data on a standard $1\frac{1}{2}$-mil by $\frac{1}{2}$-in. polyester-base magnetic tape in the binary-code decimal digital format. Automatic data recording would eliminate the inefficient and time-consuming preparation of input data from the accelerometer recordings of underwater motions. The DAS tape can be directly read by the computer in the calculation of the drag energies.

References

[1] Trout, O. F. Jr., Loats, H. L., Jr., and Mattingly, G. S., "A Water-Immersion Technique for the Study of Mobility of a Pressure-Suited Subject under Balanced-Gravity Conditions," TND-3054, Jan. 1966, NASA.

[2] Schmitt, T. J., "Wind-Tunnel Investigation of Air Loads on Human Beings," Rept. 892 (Aero 858), Jan. 1954, David W. Taylor Model Basin, Navy Dept.

[3] Lamb, G. A., "Digital Acquistion System," SC-888, Rev. 1, July 1965, AiResearch Manufacturing Div., Garrett Corp., Los Angeles, Calif.