THE USE OF ANALYTICAL METHODS TO MAXIMIZE THE PERFORMANCE OF DIVERS' BREATHING APPARATUS

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Abstract

The use of computer simulation in the design, development, and testing of complex military hardware systems has become increasingly widespread throughout the research and development community. A breathing system simulator for diver life support equipment has been developed which makes possible the modular "construction" of any conceivable breathing gas system from a bank of computer memory-resident components. This paper discusses the application of this analytical tool to optimize the conceptual design of an advanced diver underwater breathing apparatus. Design and environmental parameters are evaluated to determine their effects on the overall system performance. A "best" design is proposed based on this analysis method for a lung-powered breathing apparatus.

1. Introduction

The most crucial element in a diving operation is reliable life support. Safer, more efficient life support systems have challenged designers of diving equipment throughout man's history of subsea operations. In particular, the quest for lighter, more mobile, self-contained diving systems has created the ultimate challenge of providing the diver with total freedom from surface support.

The coupling of computer simulation methods with the unique diving system expertise and data base at NCSC has produced a new tool for the analysis and design of underwater breathing gas systems. A breathing system simulator has been developed which makes possible the modular "construction" of any conceivable breathing gas system from a bank of computer memory-resident components. This simulation model can be exercised to predict the behavior of conceptualized systems when conjoined with a man working and breathing within a user-specified range of underwater environmental conditions. This tool is expected to significantly reduce the cost and time required for the development of new diving

Figure 1: Simplified breathing system flow circuit

systems, to drastically reduce the testing required in the development and modification phases of new and existing systems, and to provide a single, easily accessible repository for system and component characteristics of existing and developmental diving systems.

2. Simulation Modeling Techniques

Model Concept. The model is based on a concept of "nodes" (places in the flow circuit where mass might conceivably accumulate) connected by "components" that affect the flow in some fashion. Figure 1 illustrates this concept with a highly simplified representation of a breathing system flow circuit. Nodes are identified in the figure with circled numbers and components with boxed numbers.

An obvious example of a node is the helmet, as reflected in the figure. A supply valve is an example of a component. Occasionally, application of these definitions to a portion of the system is not so clear. A hose is an example of such a case. Mass can accumulate at any "point" in the hose, and every element affects the flow in that it causes some pressure loss. For elements such as this, a conventional approach will need to be

defined. An approach that works for the hose case is to consider it as both a node and a component. Its accumulating character is represented by volumes and its pressure loss character by restrictions, as shown in Fig. 2. In the limit, an infinite number of each would exactly represent the nature of a hose. Practically, one volume and one restriction might be sufficient for the accuracy required.

Figure 2: Hose volume/restriction representation

Basic Principle. The fundamental principle on which the model is based is the conservation of mass. For an increment of time δ ,

$$\delta (\sum \dot{m}_{in} - \sum \dot{m}_{out}) = \Delta m \quad (1)$$

where

$\sum \dot{m}_{in}$ = the total rate of input of mass to a node (determined by a component)

$\sum \dot{m}_{out}$ = the total rate of output of mass from a node, and

Δm = the accumulation of mass at a node during time increment δ .

Nodes. For any node, the accumulation of mass Δm can be expressed in terms of density of gas in the node and the node's volume, as

$$\Delta m = \Delta(\rho V) = \rho \Delta V + V \Delta \rho \quad (2)$$

where

ΔV is the change in volume during time increment δ and

$\Delta \rho$ is the change in density during time increment δ .

Thus, if the node is extensible (as, for example, a breathing bag) but the fluid is essentially incompressible (as, for example, Heliox at 2000 FSW when experiencing pressure changes of a few centimeters of water),

$$\Delta m_{BB} = \rho \Delta V$$

since $\Delta \rho$ is negligible.

On the other hand, a CO_2 canister used at shallow depths might have negligible volume change but overriding mass accumulation due to density change, as

$$\Delta m_{cc} = V \Delta \rho$$

since ΔV is negligible.

For all nodes so far investigated, it has been found that volume changes and density changes are best expressed in terms of pressure. For the kinds of (relatively) rapid pressure changes occurring in breathing systems, a polytropic relationship between density and pressure is assumed.

$$\frac{\rho'}{\rho} = \left(\frac{P'}{P} \right)^{1/n}$$

where

ρ = density,

ρ' = density after time increment δ

P = pressure, and

P' = pressure after time increment δ

n = polytropic exponent

Then

$$\frac{\rho + \Delta \rho}{\rho} = \left(\frac{P'}{P} \right)^{1/n}$$

or

$$\Delta \rho = \rho \left[\left(\frac{P'}{P} \right)^{1/n} - 1 \right] \quad (3)$$

A perfectly elastic breathing bag, for example, would have its volume and pressure related by

$$V = V_0 + C(P - P_0)$$

where

V = volume,

V_0 = initial volume at P_0

C = constant of proportionality, and

P_0 = initial pressure,

or

$$\Delta V = C \Delta P = C(P' - P).$$

Combining these two for such a breathing bag would give (applying equation (2))

$$\Delta m = \rho C(P' - P) + [V_0 + C(P - P_0)] \rho \left[\left(\frac{P'}{P} \right)^{1/n} - 1 \right]$$

Components. Components dictate the flow into or out of a node. A simple fixed valve has its flow and pressure loss related by the usual (turbulent) expression

$$P_u - P_d = K \rho \frac{V^2}{2g_c},$$

where

P_u = upstream pressure,

P_d = downstream pressure,

K = a loss coefficient,

v = velocity, and
 $2g_c$ = a dimensional constant,
 or, solved for mass flow rate

$$\dot{m} = \sqrt{2g_c \rho A^2 \frac{P_u - P_o}{K}}$$

where

A = effective area of valve.

Other components might have more or less simple relationships between mass rate and pressure difference. A special case would be the input of a diver breathing into a helmet. For example, if his breathing pattern were assumed to be sinusoidal we can write

$$\dot{m} = \rho \pi \overline{RMV} \sin 2\pi \omega t$$

where

$\overline{RMV}$ = respiratory minute volume,
 ω = frequency, and
 t = time.

Such an input makes for a time-dependent flow situation.

Using the aforementioned means to calculate incoming and outgoing mass flow rates for individual nodes, a conservation of mass equation (equation (1)) can be written for each node in the breathing circuit. These equations will include the density/pressure relations arising from the polytropic assumption (equation (3)) and the volume/pressure characteristics of the volume as well as the flow rates expressed in terms of pressure differences and other quantities. This set of simultaneous equations will be soluble for the values of nodal pressures after a small time increment, δ .

A more complete discussion of this concept development was given previously by Sexton and Nuckols.

3. Model Application

The Naval Coastal Systems Center is presently involved in the concept development of a new Underwater Breathing Apparatus (UBA) which is intended to provide a totally integrated life support system for shallow diving. This system, shown conceptually in Figure 3, includes all equipment worn by the diver and requires neither an umbilical to the surface, nor surface support. All items of equipment are planned to incorporate state-of-the-art technologies.

The diver's back pack houses a closed cycle rebreather incorporating several innovative concepts to provide performance levels superior to conventional systems. Parallel scrubber canisters are used in the breathing loop, one containing

Figure 3: Shallow depth diving system life support backpack

potassium superoxide (KO_2) and the other lithium hydroxide ($LiOH$). Potassium superoxide, in addition to absorbing CO_2 , also generates oxygen as a by-product of the chemical reaction with the diver's exhaled gases, which is used for metabolic oxygen makeup. An oxygen sensor and logic circuit controls the O_2 level of the diver's inspired gas by actuating a 3-way valve to direct breathing gas flow through either the KO_2 or $LiOH$ canister. A CO_2 sensor warns the diver of an impending buildup of carbon dioxide in this breathing circuit. When coupled with an adequate thermal protection capability, presently under separate development, this advanced life support system will be able to support mission durations of 6 hours at 450 FSW in 29 degrees F water.

4. Comparison of Systems Concepts

Fourteen breathing circuit concepts were investigated using the simulation method discussed above. System characteristics for each model were predicted under varying environmental conditions such as depth; during varying work conditions, such as diver ventilation rate (RMV), breathing rate, and tidal volume; as well as, during application of various modifications to the basic component arrangement of the breathing apparatus design. Standard performance

Figure 4: Schematic of breathing apparatus concepts

goals of peak inhalation/exhalation pressures (P-P) and external work of breathing (W.O.B.) were used to compare the system concepts². Minimum values of P-P and W.O.B. are sought to ensure that the UBA is not a limiting factor in diver performance. Figure 4 shows circuit schematics of 3 of the 14 system concepts (concepts 12, 13, and 14) which were considered for the UBA design. Concept #12 is a closed-cycle rebreather featuring a dry backpack with an integrated helmet. The diver's exhaled breath is vented into his helmet from the oral/nasal mask, where it traverses directly to the dry backpack through a convoluted neck dam. Inhaled gases are pulled back to the oral/nasal mask through a return breathing hose following carbon dioxide absorption in the scrubber canister and oxygen replenishment. Concepts #13 and #14 have identical backpacks (either wet or dry) with a compliant volume which is always being acted upon by the ambient water pressure. A micro-porous membrane filter is included in the circuit to trap all caustic solutions or dust particles from the CO₂/O₂ generator canisters. In concept #13, the diver inhales via breathing hose and exhales into the helmet. Conversely, in concept #14, the diver inhales from the helmet and exhales via breathing hose to the backpack.

Figure 5 compares the oral/nasal pressures and neckdam volumes predicted by the simulation models for the three concepts when a sinusoidal breathing pattern is applied at a simulated depth of 450 feet of seawater (FSW) and a respiratory minute volume (RMV) of 62.5 liters/min. Additionally, a typical plot of the oral/nasal pressure versus the lung tidal volume is shown for the three concepts. The area enclosed by each "breathing loop" defines the amount of work (W.O.B.), usually given in KG-M/liter, that the diver must spend in breathing against the external resistance of the life support circuit. Note that concept #14 shows the lowest W.O.B. and peak-to-peak pressures (P-P) for all three concepts at 450 FSW.

For conditions other than 450 FSW, 62.5 RMV, or variations in system design parameters (neckdam compliance, canister resistance, etc.) the simulation model is particularly helpful in evaluating the effects of these variations on system W.O.B. and P-P. Figure 6 shows graphically the effects of neckdam compliance, the inverse of neckdam stiffness, on the system performance of the three concepts. For concept #12, which derives its system compliance only from the elastic neckdam, neckdam stiffness shows the most significant effect on W.O.B. Figure 7 shows the effects of diver respiratory minute volume on system performance. Concept #14 shows consistently lower W.O.B. and P-P across the range of RMV's analyzed. Concept #13 shows a lower P-P than concept #12 in all cases, but also consistently has higher W.O.B.'s. A similar trend was observed when investigating the effects of depth, canister resistance, and filter resistance on the system performances.

Figure 5: Concept performances under standard conditions

5. Discussion

This analysis indicates that a UBA concept similar to #14 has the lowest W.O.B. and P-P values of the three systems. Likewise, it was observed that neckdam compliance could be effectively reduced to zero (no helmet accumulation) without significantly increasing system W.O.B. or P-P. In addition, the backpack volume showed no effect on system performance for concept #14. This would indicate that the backpack dry volume can be reduced to zero (wet backpack), with the canister exhaust ducted to the filter, without significantly affecting system performance.

Figure 6: Effect of neckdam compliance on system performances

Based on this parametric evaluation on the 14 different concepts a concept simulation was derived which combines the beneficial characteristics of past concepts. Thereby, this "recommended" concept, Figure 8, is shown to have the lowest W.O.B. and P-P pressures of all concepts analyzed to date. The primary features of this concept (concept 15) are:

Figure 7: Effect of diver breathing rate on system performance

- COMPLIANT VOLUMES ON EACH SIDE OF MAJOR RESISTANCES
- MINIMUM DRY BACKPACK VOLUME
- NO HELMET COMPLIANCY (LITTLE OR NO HELMET VOLUME)
- LOCAL COMPLIANT VOLUMES AS CLOSE AS POSSIBLE TO CENTROID OF LUNG

Figure 8: Recommended concept to minimize peak-to-peak pressures and work-of-breathing

a. Compliant volumes are located on both sides of major circuit resistances (CO_2 scrubber and gas filter).

b. A micro-porous membrane filter is included in the circuit to trap all caustic solutions or dust particles from the CO_2 scrubber/ O_2 generator.

c. Helmet compliancy is minimized. The use of oral/nasal mask with low helmet volume and compliance minimizes mask leakage and helmet pistoning.

d. Backpack volume is minimized whether wet or dry.

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REFERENCES

1. Sexton, P.G., Nuckols, M.L., "Computer Simulation of Breathing Systems for Divers", Journal of Engineering for Industry, Vol. 105, No. 1, pp. 54-59, February 1983.
2. Middleton, J. R., Thalmann, E. D., "Standardized NEDU Unmanned UBA Test Procedures and Performance Goals", Navy Experimental Diving Unit Report No. 3-81, July 1981, AD 3A105609.