Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Design of an Articulated, 1-Atm, Undersea Suit

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THE development of a wide spectrum of devices and systems capable of functioning effectively at great depths is now being considered. Included is the 1-atm, articulated, pressure-resistant suit which will allow a diver to remain at normal atmospheric pressure while working under high hydrostatic pressure. The suit, moreover, can be effectively insulated and equipped with a self-contained life support system. Based on the experience gained in the development of pressure-protective suit systems for use in both space and space atmospheres, the Space Sciences Laboratories of Litton Industries established that the basic requirements for a protective suit system involved: 1) safety, 2) mobility, and 3) comfort.

From an engineering point of view, mobility is the most difficult requirement and is primarily considered here. The human body contains bones, jointed by articulations that allow rotations and deflections, which are shaftlike and hingelike respectively. Complex motions allowed by ball-and-socket joints (shoulder, hip) can be resolved into simple motions of both types. The technical success of a rigid, articulated suit requires joints that can move like the body articulations with minimum friction and volume variation. The number, position, and orientation of the articulations must correspond quite closely to corresponding human anatomical articulations.

The degrees of freedom found necessary for adequate mobility require 13 different mechanical articulations. Nine are hingelike, two are rotational, and the remaining two can be mechanized in different ways since the complex anatomical motions are resolved into rotations about reference axes that lie at inaccessible points inside the body (shoulder, hip).

In Litton suit designs, both for space and underwater, hinge-like or flexural motions are permitted by constant-volume convolute joint systems and the rotational motions by rotary seals. The proper combination of the two allows adjusting the joint systems to conform to the human anatomy and to place the geometrical axis of the structure in coincidence with the anatomical axis of the articulation.

Technical problems in adaptation of these joint concepts from space suit to the diving suit are severe, primarily because the specific pressure difference is 3.7 to 5 psi in the former case and 270 psi in the latter.

Rotary Seal

The design of the rotary seal is based on conceptual separation of the forces that tend to close the seal and prevent a leak from the forces that tend to cause friction, which permits optimization of geometry and first-order compensation of forces. As a result, the net torque required to turn the seal increases less than 30% for a change of applied pressure from 0 to 20 atm. This is compatible with the muscular strength of the enclosed man.

Figure 1 shows the basic structure of a rotary seal for the articulated diving suit. The major applied force is axial thrust, equal to the applied pressure P multiplied by the area of the seal πR^2. The axial thrust is absorbed by the main thrust bearing. A row of smaller bearings forms an angular contact that controls the concentricity of the elements and prevents separation of the seal under no-load conditions.

The seal proper is formed at the interface between a sealing washer of relatively soft and slippery material (Teflon) and a sealing lip of ground, lapped and polished, hardened steel. The mating parts are forced together with a pressure sufficient to deform plastically the softer material, so that it flows and fills the microscopic surface irregularities of the harder material. The major component of friction is due to flow of the material out of the way of the microscopic prominences of the harder material and into the microscopic depressions. The sealing washer is backed by an elastic washer of soft rubber which is squeezed at assembly sufficiently to create a preload pressure P_i that produces the deformation of the plastic material required to form the seal. The elastic washer is exposed on one side to the pressure of the external environment. When this pressure increases above the internal pressure, the difference is applied directly on the sealing lip as the fluid tries to push the seal apart and, indirectly, through the elastic washer as the elastic washer transmits the applied hydrostatic pressure. With current dimensions, the increasing hydrostatic pressure springs the seal in order to maintain the pressure on the sealing lip constant. The result is $P_s - P = P_i$, and the sealing P_s is always higher than the applied pressure P by an essentially constant amount equal to the preloading pressure P_i. The increase in the thrust load with hydrostatic pressure can also be partially counteracted by undercutting the sealing lip, so it is supported by what amounts to a very stiff diaphragm so machined that the sealing lip tends to deflect away from the sealing washer by the same amount by which the sealing elements tend to come together. The torque T required to turn the seal is the tangential force times the radius. The tangential force equals the coefficient of friction K times the contact area A and the net applied

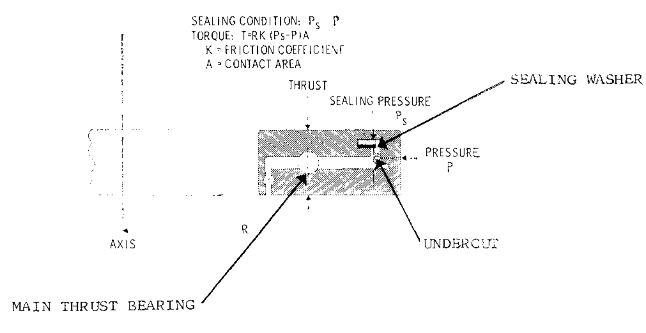

Fig. 1 Basic structure of rotary seal.

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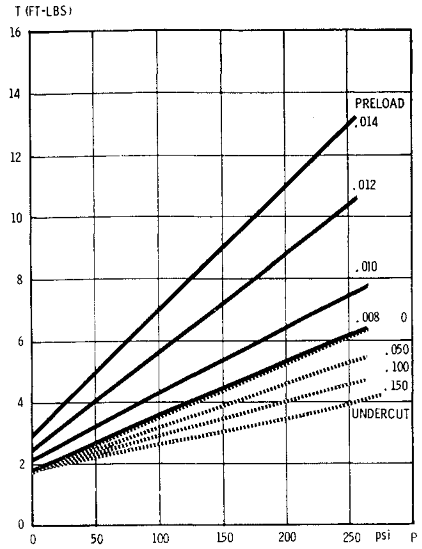

Fig. 2 Typical torque test results for 4-in.-diam. rotary seal.

pressure, viz.,

$$T = RKA(P_s - P) = RKAP_i$$

Since P_i is essentially constant, so also is T. A is the area of contact between the sealing lip and the sealing washer: $A = 2\pi R d$, where d is the radial thickness of the sealing lip. The torque can be made as low as desired by making d thin within practical limitations, which is acceptable for the intended application.

Figure 2 shows typical test results for a 4-in. seal intended for the wrist pronation-supination axis of a diving suit. The effects of varying the preloading pressure P_i, as well as the effects of the lip undercut, are shown.

Convolute Joint

A typical hingelike articulation, embodying the rolling convolute principle to an elbow joint, is shown in Fig. 3. It consists of a number of metal hoops nesting in each other. A rubberized fabric sleeve, held between the hoops, is the pressure barrier. The hoops contain and shape the fabric, so that folds or convolutions are formed between the hoops. The axial load is pure compression. When the articulation is flexed, the fabric convolutions roll in and out of the spaces between the hoops, and the symmetry is such that the volume increase on the side that expands is exactly balanced by an equal volume loss on the side that contracts. The net volume change is zero, and no work is done against external pressure, so the only torque required to bend the articulation is associated with the rolling friction of the fabric and the internal gearing.

The elbow convolute has been tested with encouraging results at 240 psi. It was subsequently redesigned to improve performance, and an entire arm was then produced and tested. The elbow joint was, in addition, tested to destruction to develop confidence levels regarding materials and fabrication techniques used. In this test, the joint met the design specifications, thoroughly proving the intrinsic worth of the convolute principle. The design improvements already incorporated will allow future elbow joints to withstand substantially greater pressures.

In the construction of an entire articulated arm or leg, several convoluted joints of similar design, but of different sizes, are integrated in an assembly that follows closely the shape of the human body and places the axis of each articulation near the corresponding anatomical point. The articulations are connected by rigid sections that can be interchanged with others of different length for adjustment to the individual diver's measurements.

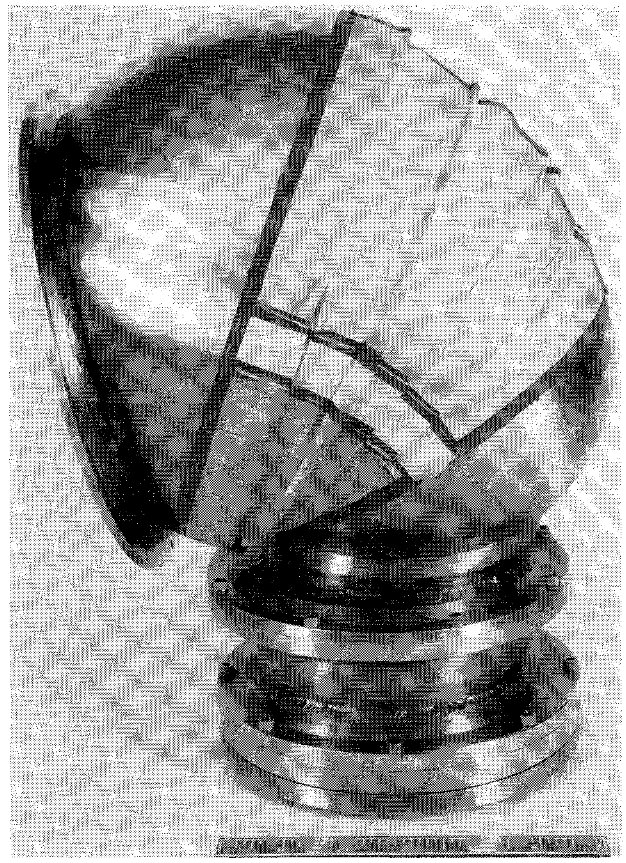

Fig. 3 Single-axis constant-volume elbow joint.

The arm and leg articulations are, in turn, attached to a torso and helmet assembly into which the life support and communications systems are incorporated. Sufficient instrumentation to allow the diver to orient himself on the bottom will also be provided. An artist's representation of the assembled suit is shown in Fig. 4.

Fig. 4 1-atm diving suit.

Concluding Remarks

The design efforts to date have centered on the development of the arm articulations in order to prove feasibility. Current efforts are concentrated in the development of a workable articulated glove. The complexities of the hand articulations, because of the small size of the joints and the interference problems between adjacent joints, make this a most complex task. However, preliminary model studies of metacarpal and thumb joint systems indicate that a workable solution can be developed.

Announcement: Change in Style for References in AIAA Publications

The Committee of Engineering Society Editors, of the Engineers Joint Council, has recommended a standard style for references in engineering publications. In the interest of reducing the burden on authors and editors and minimizing confusion, the AIAA Publications Department has decided to follow the recommended style. Examples of the new style will be found below and on the inside back cover of all AIAA journals. The changes will be effective with manuscripts scheduled for the January 1968 issues and thereafter.

Example—Journals

Walker, R. E., Stone, A. R., and Shandor, M., "Secondary Gas Injection in a Conical Rocket Nozzle," *AIAA Journal,* Vol. 1, No. 2, Feb. 1963, pp. 334–338.

Examples—Books

Turner, M. J., Martin, H. C., and Leible, R. C., "Further Development and Applications of Stiffness Method," *Matrix Methods of Structural Analysis,* 1st ed., Vol. 1, Macmillan, New York, 1964, pp. 203–266.

Segrè, E., ed., *Experimental Nuclear Physics,* 1st ed., Vol. 1. Wiley, New York, 1953, pp. 6–10.

Example—Reports

Book, E. and Bratman, H., "Using Compilers to Build Compilers," SP-176, Aug. 1960, Systems Development Corp., Santa Monica, Calif.

Example—Transactions or Proceedings

Soo, S. L., "Boundary Layer Motion of a Gas-Solid Suspension," *Proceedings of the Symposium on Interaction between Fluids and Particles,* Institute of Chemical Engineers, Vol. 1, 1962, pp. 50–63.