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Abstract
Hydraulic hoses are used in industrial machines to transmit power. These hoses have a physical stiffness that depends upon the hose size and type. If a computer model is used to predict the path a hose will take through a machine, accurate physical stiffness properties are required for the hose. These stiffness properties are not available from hose manufacturers and hose test methods are scarce in the available literature. This paper describes methods used for testing the bending stiffness, torsion stiffness, and axial stiffness of hydraulic hoses. Plots of the stiffness data are given for a sample hose.

Keywords
VRAC, Hydraulic hose, Testing, Stiffness

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STIFFNESS TESTING OF HYDRAULIC HOSES

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ABSTRACT

Hydraulic hoses are used in industrial machines to transmit power. These hoses have a physical stiffness that depends upon the hose size and type. If a computer model is used to predict the path a hose will take through a machine, accurate physical stiffness properties are required for the hose. These stiffness properties are not available from hose manufacturers and hose test methods are scarce in the available literature. This paper describes methods used for testing the bending stiffness, torsion stiffness, and axial stiffness of hydraulic hoses. Plots of the stiffness data are given for a sample hose.

INTRODUCTION

Hydraulic hoses are reinforced hoses used to transmit high-pressure hydraulic fluid throughout machines. These hoses are typically constructed of rubber and reinforced with one or more layers of wire. The physical stiffness of hoses varies greatly with their size and pressure rating. Hose stiffness can also be affected by wear-resistance coverings that are bonded to the outside of some hoses. Hose manufacturers perform rigorous tests on the hoses to determine their pressure ratings and durability but surprisingly few tests have been performed to determine the physical stiffness properties of the hose.

The need for hose stiffness properties arises when one wants to model the path a hose will take through a machine. When machine designers are routing hoses through a new machine, they need to control the path of the hose in order to keep it away from moving parts, extreme temperatures, or other things that may decrease the life of the hose. Currently, many hose routes are designed after the first prototype of a new machine is built, simply by experimenting with different hoses until one works. It is desirable to perform the hose routing earlier in the product design process to decrease time-to-market and produce better hose routes. However, to perform hose routing before the first prototype build, designers must have a computer model of the hose so they can predict the path a hose will take due to its stiffness properties, weight, end conditions, and clamping constraints. ADAMS, a commercial dynamic simulation package, has been used to model hose paths [1,2,3]. This model requires several physical properties of the hose that are not commonly available. This paper describes the properties of the hose that are required in order to model the hose path and methods that were used to test for those hose properties. Stiffness plots are given for a sample hose.

DESCRIPTION OF REQUIRED PROPERTIES

The stiffness properties required to model the hose shape are the bending stiffness, torsional stiffness, and axial stiffness. If pressurized hoses are to be modeled, the change in length under pressure must be measured. Change in length under pressure occurs in most reinforced hoses due to the contraction or expansion of the reinforcing wire. Also needed are weight per unit length, inside diameter, and outside diameter, which can be obtained from hose manufacturers.

In order to test for the stiffness properties of the hose, assume that the hose has constant bending (K_B), torsional (K_T), and axial stiffness (K_A) as given by the following linear equations.

[1] Corresponding Author

Bending: $M = K_B \bullet ?$ (1)

Torsion: $T = K_T \bullet f$ (2)

Axial: $P = K_A \bullet d$ (3)

In Eq. (1), *M* is the bending moment applied to the end of the hose and ? is the angle the hose bends. In Eq. (2), *T* is the torque applied to the end of the hose and *f* is the angle of twist that results. Finally, in Eq. (3), *P* is the axial force applied to the hose and *d* is the amount of axial deflection. For an illustration of the applied forces and moments, see Fig. 1.

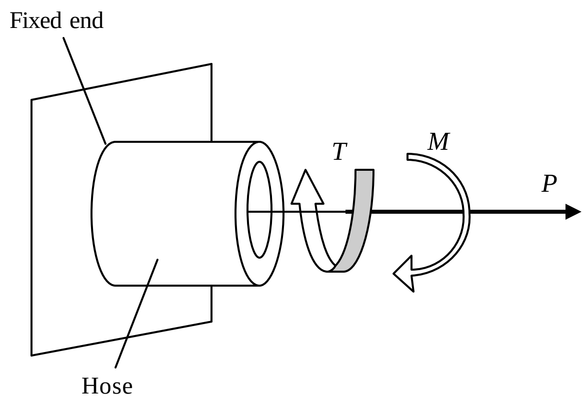

Figure 1. Force, torque and moment application.

In order to solve for the hose path, the values of ?, *f*, and *d* are needed, given the bending moments, torques and forces applied to the hose. Instead of using K_B, K_T, and K_A, ADAMS requires the stiffness be input in terms of *E* (Young's modulus), *A* (cross section area), *I* (moment of inertia), *J* (polar moment of inertia), and *G* (shear modulus). In order to convert K_B, K_T, and K_A, to *E*, *A*, *I*, *J*, and *G*, consider the following formulas.

Bending: $$M = \left(\frac{EI}{L}\right) q$$ (4)

Torsion: $$T = \left(\frac{GJ}{L}\right) f$$ (5)

Axial: $$P = \left(\frac{EA}{L}\right) d$$ (6)

These equations are only valid for small deformations. Note that Eq. (4) depends on the configuration of the bending test setup. Since our bending test setup is equivalent to a cantilever beam with a moment on the end, Eq. (4) is the correct form. It is clear from Eqs. (1) through (6) that the following relationships are true.

Bending: $EI = L \bullet K_B$ (7)

Torsion: $GJ = L \bullet K_T$ (8)

Axial: $EA = L \bullet K_A$ (9)

Equations (7) through (9) express the relationships that are required to obtain the input information for the ADAMS solution. If hydraulic hoses were linearly elastic, isotropic, and homogeneous, then the stiffness properties of the hose could be expressed in terms of only *E*, *G*, and the dimensions of the hose cross-section. This would require only two tests to be performed to determine stiffness. However, hoses are composed of non-homogeneous material so stiffness values must be calculated for all three directions.

SUMMARY OF PREVIOUS HOSE TESTING

Before performing hose tests, the hose manufacturers were surveyed to obtain the stiffness properties. Stratoflex, Gates, and Aeroquip were the only hose manufacturers that had tested for bending stiffness. All three manufacturers used some type of cantilever test in which one end of the hose was clamped and a force was applied to the free end. This type of test configuration causes a shear force in the hose and also subjects the hose to an axial force if the force is not applied very carefully. None of the hose manufacturers had property data on torsion or axial stiffness.

In order to get the most accurate bending stiffness data, a test that produced only a bending moment in the hose was needed. Budney and Bouey [4] presented a clever test setup for testing hoses that fit this criterion and this was used as the basis for the bending test setup presented here. No existing methods for testing hoses axially or in torsion were found. Methods for these two tests were developed, using ASTM standard test practices whenever possible, and are presented in this paper. See Appendix A for a listing of applicable ASTM standards. Some torsion testing ideas from Oess [5] were also used.

TEST METHODS

Three sets of stiffness tests were performed for each hose: bending stiffness, torsional stiffness and axial stiffness. The bending stiffness and torsional stiffness values were tested at both zero pressure and full rated pressure. Three hose samples were used for each test and their properties were averaged. The bending stiffness test is the most important of the three stiffness tests because during normal use in industrial machines, hoses are subjected to bending but not to torsion or axial loads. If torsion or an axial load is applied to a hose in an actual application, the hose is likely to fail. Tests for torsion and axial stiffness were still needed, however, since these values are required by the computer model. The following sections will describe the test methods used and a sample stiffness graph will be given for each test. Change in length under pressure was also recorded for each type and size of hose that was tested.

The hoses that were tested ranged in size from 0.25-inch to 1-inch inside diameter and in working pressure from 3000 psi to 4000 psi. Hose manufacturers also specify a minimum bend radius, which is the smallest radius that the hose can be bent into without reducing the useful life of the hose. Minimum bend radius gives some indication of the bending stiffness of a hose and usually depends on the size and on the internal construction of the hose. The hoses tested for this research ranged from 4-inch minimum bend radius to 12-inch. The hose used as an example in the following sections of this paper had an interior diameter of 5/8 inch and a pressure rating of 4000 psi.

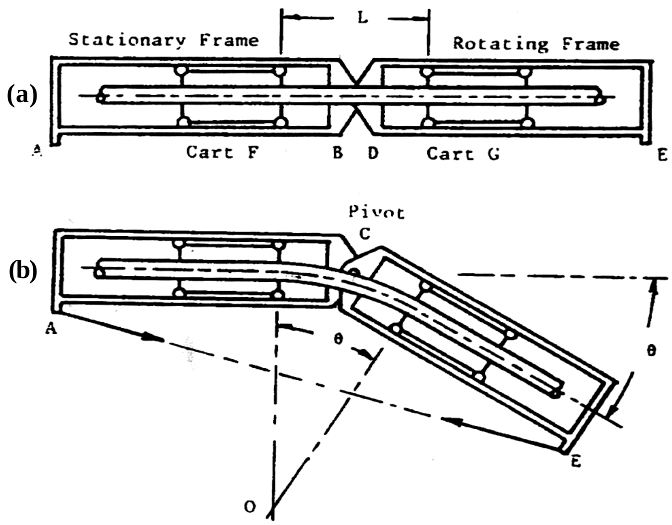

Figure 2. Bending test rig (Budney and Bouy [4])

Bending Test

The bending test rig was built based on a paper by Budney and Bouy [4]. This test is configured so that no shear forces or axial forces occur in the hose. The test fixture loads the hose in a way that is equivalent to applying a bending moment to the free end of a cantilevered hose. The length of the hose test specimen was chosen such that the rated minimum bend radius for the specimen was reached when the hose was bent into a quarter-circle.

The test rig drawn in Fig. 2(a) shows both ends of the hose rigidly attached to two movable carts. The carts are placed in two guiding frames. One frame is held rigidly while the other frame is free to pivot about a fixed point. In order to perform the test, a force was applied between points A and E, which produced a torque on the rotating frame and thus a pure bending moment on the hose. The bending moment in the hose is equal to the force applied between A and E multiplied by the perpendicular distance from AE to point C. Figure 2(b) shows the hose deflected by an angle of q. The angle was measured as the force was applied and the value for the bending stiffness, K_B, was determined from the slope of the moment vs. angular deflection curve. Specimens were tested both pressurized and unpressurized. Hoses were pressurized with a hydraulic hand pump attached to the specimen in a way that didn't interfere with the test.

Figure 3 shows the actual test fixture in use for an unpressurized specimen. The test fixture was built very carefully in order to perform as designed and produce only a bending moment in the specimen. A low friction linear motion system was used for the cart and rail. The wheel bearings for the carts were tuned so that the rolling resistance was very low. Before each test, the fixture was leveled so that gravity forces would not affect the test data. The force applied to the hose was measured using a force transducer as shown in Fig. 3. The angle of the rotating rail was measured by a rotational potentiometer, located on the bottom of the pivot shaft. The moment on the rotating rail was calculated using the measured angle and force and by analyzing the 4-bar mechanism overlaid on Fig. 3. Figure 4 shows a graph of the results for a sample hose.

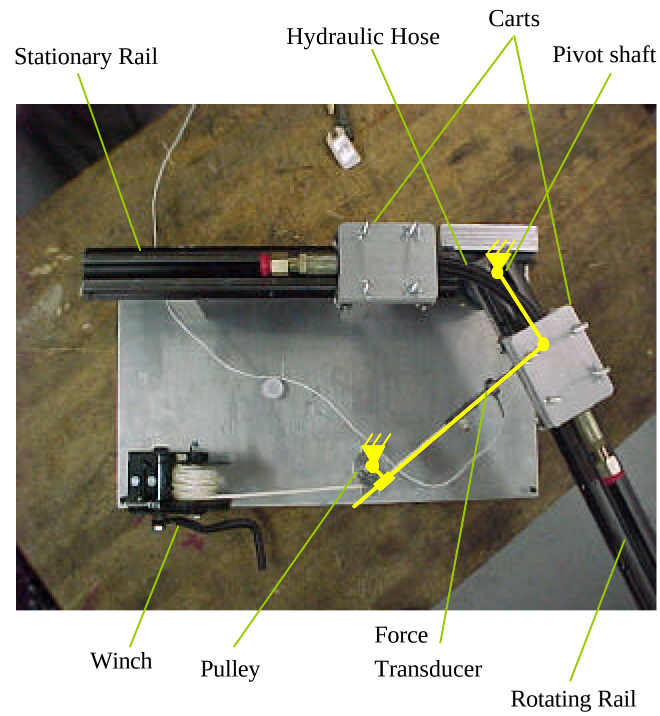

Figure 3. Bending test rig with loading mechanism overlaid.

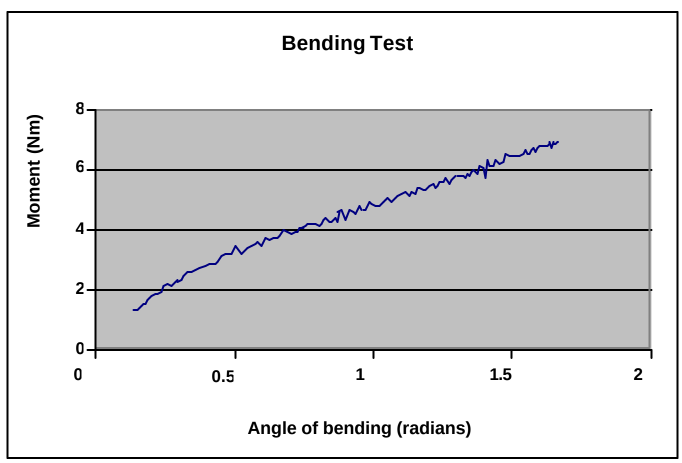

Figure 4. Bending test data for a sample hose.

Torsion Test

The torsion test was performed by fixing one end of a short hose and applying a torque to the other end. A length of six times the interior diameter was used for unpressurized hoses and eight times the interior diameter was used for pressurized hoses. This length was determined experimentally. Hoses that were longer than the length specified above would coil up like a spring when subjected to a torque. The longest specimens possible were used in order to reduce end effects.

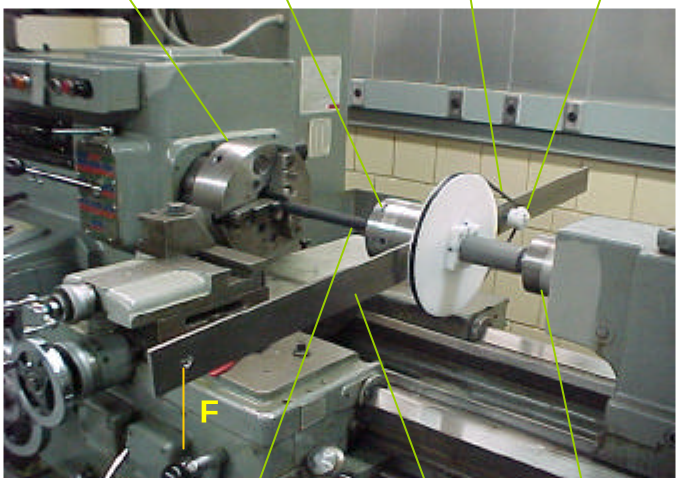

Figure 5. Torional test rig.

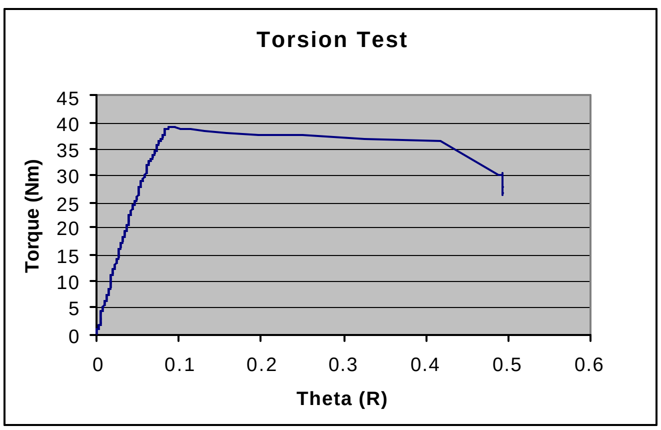

Figure 6. Torsional data for a sample hose.

The torsion test setup was designed to mount onto a standard metal working lathe. Figure 5 shows the actual torsion test rig mounted on a lathe. The lathe chuck was used to grip and hold one end of the hose stationary. A chuck assembly that gripped the free end of the hose specimen was designed to fit into the tailstock of the lathe. A linearly increasing torque was applied to the hose by increasing the force on the end of the moment arm (F in Fig. 5). A rotational potentiometer was used to measure the angular displacement. Angular displacement of the free end of the hose was plotted as a function of the applied torque. The torsional stiffness, K_T, was calculated from the slope of the torque vs. angular displacement curve. Specimens were tested both pressurized and unpressurized. Hoses were pressurized by a hydraulic hand pump attached to the specimen with a hose routed through the hollow center of the stationary lathe chuck. Figure 6 shows a graph of the data from a sample hose.

Axial Test

The axial test was performed by placing a short section of hose in compression. Figure 7 shows the axial test rig, which is a standard Instron compression test machine. The length of the specimen was approximately the same as its outside diameter so that buckling would not occur when the specimen was loaded. A hose specimen was placed between the platens of a compression test machine. Small pieces of sandpaper were placed on each end of the specimen to keep the ends from spreading. A compressive force was applied along the axis of the hose and the resulting deflection was measured. The force was increased until enough data were taken to form a plot of displacement versus force. The axial stiffness, K_A, was determined from the slope of the displacement versus force graph. Figure 8 presents a graph of the axial deflection results for a sample hose.

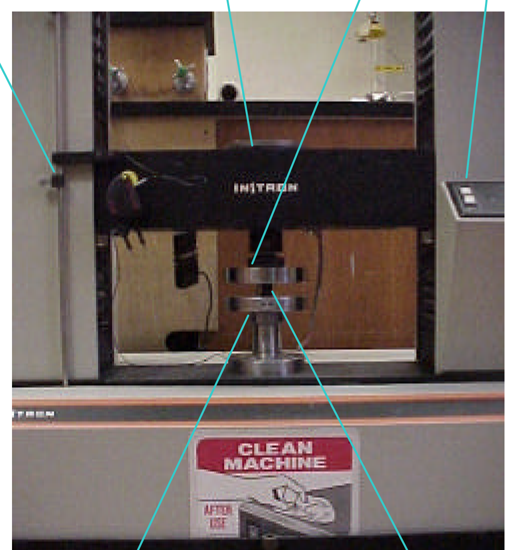

Figure 7. Axial test rig.

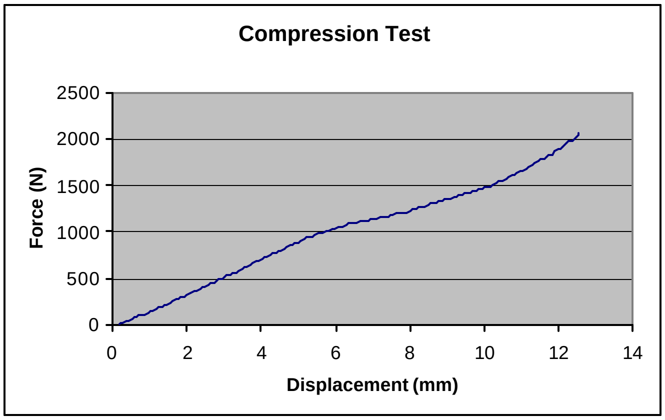

Figure 8. Axial test data for a sample hose.

Change in Length Under Pressure Test

The test for change in length under pressure was a simple test to perform. The hose length was measured at the beginning of the test, then the hose was pressurized and the hose length was measured again. Change in length under pressure was calculated as the percent change in hose length when the hose was pressurized.

DATA ANALYSIS

The axial, bending, and torsion tests produced plots of force, torque, or moment versus deformation. In each case, we were interested in the slope of these plots for small deformations because the ADAMS hose model is only valid for small deformations. For most hoses, the plots were relatively linear in the area close to zero deformation so a linear regression was performed to determine the slope of that section of the plot. The stiffness values in Eqs. (1) through (3) are equal to the slopes of the regression lines. In order to calculate the stiffness in terms of E, G, I, J, and A, Eqs. (7) through (9) are used. Both pressurized and unpressurized hose data was analyzed as described above. The pressurized stiffness and unpressurized stiffness of a hose are treated as separate properties in our data. No attempt was made to determine the non-linear relationship between pressure and stiffness.

CONCLUSION

The processes used to test for the properties of hydraulic hoses were presented in this paper. The hose tests that were described were designed specifically for hoses after considering current test practices. These tests have supplied reliable mechanical properties and could be made more accurate in the future by performing additional tests with different loading rates to determine the effect of loading rates on stiffness. Also, more tests should be performed in order to determine if there is a relationship between the hose stiffness and the size and/or internal construction of the hose.

ACKNOWLEDGEMENTS

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APPENDIX A. ASTM STANDARDS.

ASTM standard number	Title
ASTM D 380 – 94	Standard Test Methods for Rubber Hose
ASTM D 575-91	Standard Test Methods for Rubber Properties in Compression
ASTM E111-82	Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
ASTM D3183-84	Standard Practice for Rubber – Preparation of Pieces for Test Purposes from Product
ASTM E 855-90	Standard Test Methods for Bend Testing of Metallic Flat Materials for Spring Applications Involving Static Loading
ASTM D 790 - 95a	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM E 143 – 87	Standard Test Method for Shear Modulus at Room Temperature