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European Journal of Advances in Engineering and Technology, 2021, 8(9):15-21

Research Article ISSN: 2394 - 658X

Fatigue Bending Endurance Evaluation of an Automotive Air Conditioner Hose

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ABSTRACT
Fatigue failures of air conditioner hoses occur due to the stresses caused by complex loads during use. We intend to investigate experimentally the relationship between the bending curvature radius of an air conditioning liquid hose and the bending fatigue lifetime as directly affected by the design of the hose. A device for measuring the bending curvature radius was developed and applied to develop a bending fatigue endurance testing device for these types of hoses, and the fatigue damage mechanisms of the hoses were studied. The fatigue lifetimes were almost inversely proportional to the axial strain due to rotational loading, except for a case with cross-sections excessively reduced by 33.3%.%. Given a large diameter reduction ratio, the inner rubber becomes excessively deformed in the cross-section of the area where local buckling occurs, with the inner rubber and reinforcing layer becoming completely destroyed along with leakage with external rubber.

Key words: Air conditioner hose, Fatigue bending endurance, Diameter reduction ratio, Fatigue damage mechanisms, Bending curvature radius

INTRODUCTION

Air conditioning hose assemblies are used to carry refrigerant and lubricant between the components of cars, typically both pressure and return lines. The larger hose typically carries cool gas and is commonly referred to as the suction hose, return hose or vapor hose. The smaller hose typically carries warm liquid and is most often called the liquid hose. Fatigue failure of these hoses occurs due to the strain and stress caused by complex loads such as bending, torsion, and tension during use. Therefore, when developing these hoses with the goal of high durability, specifications pertaining to the maximum operating pressure, maximum operating temperature, and minimum radius of curvature, among other, are prescribed [1-3].

Thus far, limited studies have been conducted on the repeated bending of hydraulic hoses and the durable lifetimes of hydraulic hoses [4-13]. For example, Evans and Manley [4] conducted a study of the correlations and interactions between the operating pressure, temperature, flow rate, pressure increment rate, bend radius, and frequency, all of which are factors affecting the durability of hydraulic hoses. They proposed appropriate test conditions for full or semi-Omega bending tests in their study. Kwak and Choi [5] conducted a study of the failure mechanisms of hoses through tests that could reproduce the combined stresses of stemming from repeated pressure, bending, twisting and temperature conditions on EPDM rubber automotive brake hoses reinforced with PVA fibers. The durability of these hoses was assessed at 370,000 cycles, and the initial damage was reported to arise at an angle of 145 degrees due to bending and torsional loads. Additionally, peeling process occurred between the cladding rubber and the PVA fiber layers. Breig [6] analyzed the wire stress of a rubber hose reinforced by a spiral wire subjected to deformable bending. He confirmed that the minimum bending curvature radius is associated with the level of wire stress. Berns [7] proposed a method for predicting the lifetime of a hydraulic hose using pressure-life curves in a manner similar to stress-life curves in mild steels through a linear cumulative damage analysis. Towle [8] proposed a fatigue life prediction program for hydraulic hoses based on linear cumulative damage theory using the load time, bending curvature radius, pressure range, and average pressure as variables.

In this study, we experimentally investigate the relationship between the bending curvature radius of an air conditioning liquid hose and the bending fatigue lifetime as directly affected by the design of the hose. To this end, a device for measuring the bending curvature radius was developed and applied to develop a bending fatigue endurance testing device for these types of hoses. The intent is to use it to evaluate the durability of these hoses derive the relationship between the radius of curvature and the bending fatigue lifetime. In addition, the fatigue damage mode of the hoses is observed to determine the cause of fatigue damage. The goal is to provide basic data necessary to develop a hose with the minimum radius of curvature considering its fatigue bending durability.

AIR CONDITIONING LIQUID HOSE

Fig. 1 presents a diagram of an automotive air conditioning system. The air conditioning liquid hose is the focus of this bending fatigue test, and the hose serves as a passageway through which refrigerants in the air conditioning system move, as shown in Fig. 1. Hydraulic or air conditioning hoses consist mainly of oil-resistant and water-resistant inner tubes on the inside, with the construction being similar to that of an automotive tire, along with reinforced layers that cover chemical fibers or a steel core alone in a mesh form, and outer tubes made of oil, weather, and wear-resistant ethylene-propylene diene copolymer (EPDM) synthetic rubber. Here, the internal and external diameters of the rubber hoses are 8 mm and 15.7 mm, respectively. Fig. 2 shows cut-away images of an air conditioning hose prior to a fatigue test. The structure of the hose consists of rubber on the inner and outer areas, as shown in Fig. 2(a), with fibers serving as a reinforcing layer between the inner and outer rubber. Also, the inside of the inner rubber is coated, as shown in Fig. 2(b). The hose is made of EPDM rubber. Fig. 3 is an enlarged photograph of the outer layer rubber. on the air conditioning hose. We confirmed that artificially pinpricks exist at approximately 12 mm intervals, as shown in the photograph. This prevents the bubbling of the outer layer of the rubber if gas or vapor accumulates between the outer layer rubber and the inner layer rubber. The holes also penetrate from the surface of the outer layer rubber of the hose to the reinforcement layer.

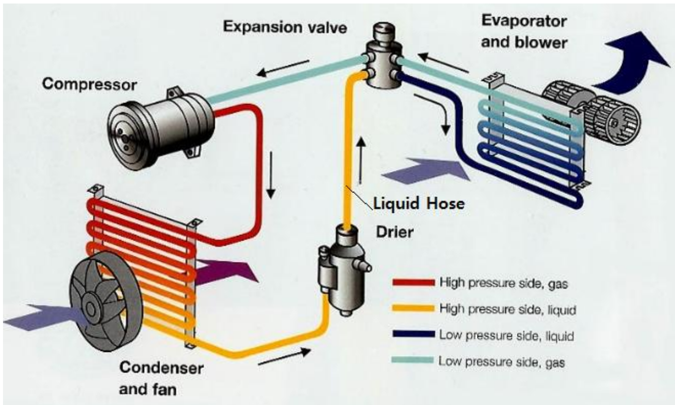


Fig. 1 Schematic of an automotive air conditioning system

(a) (b)

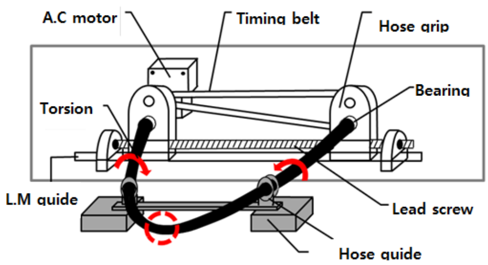
Fig. 2 Structures of an air conditioning liquid hose: (a) outer rubber and braided fabric and (b) outer and inner rubber layer with an inner coating

Fig. 3 Pinpricks on the outer layer of the air conditioning liquid hose

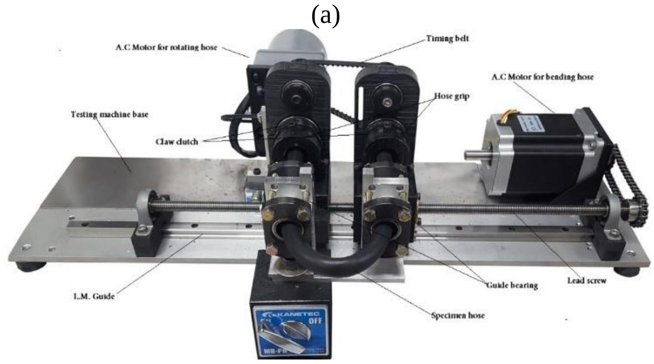
DESIGN OF THE BENDING FATIGUE TEST DEVICE

In this study, the bending curvature of the hose is measured to evaluate its effect on the fatigue lifetime under repeated bending of the rubber hose, and a testing device capable of realizing bending rotation while maintaining a constant bending curvature is designed and built. As shown in Fig. 4, the testing device consists of a curvature control system, a measurement system, a rotational speed control system, a rotational speed measurement system, and a grip that holds the rubber hose specimen. Similar to a conventional rotational bending fatigue test, the present fatigue test is such that both ends of the specimen are fixed to the grip of the test device, with one end connected to the drive axle and the other connected to the driven axle. The two axes at both ends were connected by a timing belt so that they could rotate at the same speed. Therefore, the curved section of the hose was repeatedly subjected to tensile and compressive stresses.

For the rotational speed control system, the power of the AC motor was turned on/off using an Arduino Uno board, and a speed controller dedicated to the AC motor was used to control the bending rotation speed. The fatigue rotational speed was determined using a photo-sensor, and the entire tester system was controlled by a National Instrument (DAQ 6009 board) with the LabVIEW 2010 program. National Instrument's Vision Assistant program was used to measure the radius of curvature of the hose, as shown in Fig. 5, and a web camera (Logitech Co. HD PRO WEBCAM C920) was used to acquire images of the curved hose.



(a)



(b)

Fig. 4 Testing device for the hose rotational bending experiment: (a) schematic diagram and (b) actual image

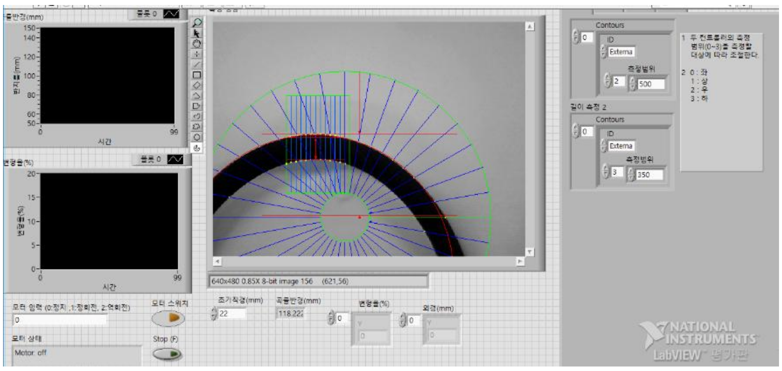


Fig. 5 Vision program for measuring the radius of curvature of the hose

Preparation of fatigue specimens and procedures

The rubber hose fatigue specimen used here was prepared by filling the inside of the rubber hose with a liquid mixture of white water-soluble paint and water and then sealing both ends of the rubber hose to facilitate visual confirmation that the rubber hose is ruptured and leaking water. The length of the specimen was 400 mm, as shown in Fig. 6, considering the distance between the center of the grip parts of the developed fatigue testing device. The rotation speed of the fatigue test was set to 15 rpm. The test conditions considered the diameter reduction ratio and radius of curvature, and the test was conducted at the corresponding radius of curvature by adjusting the location of the gripping part center of the specimen. In this study, fatigue tests were performed with a radius of curvature between 3.2 mm and 29.8 mm, corresponding to a maximum diameter reduction ratio of 33.3% to 4.3%. If the refrigerant leaks due to damage of the inner rubber layer of the hose, the leakage occurs through the pinprick hole of the outer rubber layer. Accordingly, the definition of a hose failure was not assumed to occur when the outer layer rubber burst, but rather when liquid leakage occurred in the outer rubber and the hose thus failed to function properly. In other words, the moment of that of the refrigerant leaked onto the outer layer surface at regular intervals during the fatigue test was considered to be the moment of failure.

EXPERIMENTAL RESULTS

Relationship between the diameter reduction ratio and fatigue lifetime

Table 1 summarizes the maximum diameter reduction ratio, radius of curvature, fatigue lifetime, and fatigue fracture modes of the tested air conditioning liquid hose specimens. Fig. 7 shows the relationship between the maximum diameter reduction ratio (R) and the radius of curvature (ρ) of the hose. This relationship is expressed as follows: $\rho = 36.27 - 1.95R + 0.03R^2$. As the radius of curvature decreases, the maximum diameter reduction ratio increases. In the range of approximately 5% to 15% of the maximum diameter reduction ratio, the radius of curvature decreased significantly by 60% from approximately 30mm to 12mm as the diameter reduction ratio was increased. On the other hand, in the range between 15% and 33.3% of the maximum diameter reduction ratio, the change in the radius of curvature was relatively small as the diameter reduction ratio was increased.

Fig. 8 shows the relationship between the maximum diameter reduction ratio (R) and the fatigue lifetime (N_f) of the liquid hose. It was found to be almost inversely proportional to the hose diameter reduction ratio and bending fatigue lifetime. The fatigue lifetime was 156,065 cycles when the diameter reduction ratio was 4.3%, and the fatigue lifetime was 7,273 cycles when the diameter reduction ratio was 33.3%. Fig. 9 shows the fatigue lifetime as a function of the maximum axial strain of the hose. For air conditioning hoses, the outer diameter is 15.7 mm. If the hose has a minimum radius of curvature of 19.3 mm, the maximum axial strain ε_x of the curvature corresponds to $\varepsilon_x = \frac{r}{\rho_{ave}} = \frac{r}{\rho + r} = \frac{7.85}{19.3 + 7.85} = 0.289$. Fig. 9 confirms that the axial strain and fatigue lifetime were almost inversely proportional except for a datum that caused local buckling of rubber hoses during bending loads and showed excessively reduced cross-sections by 33.3%.

Table -1 Experimental results of rotary bending fatigue tests of the liquid hose

Diameter reduction ratio (%)	Radius of curvature (mm)	Failure lifetime (N_f)	Failure modes
33.3	3.2	7,273	Water leaks through holes in the outer rubber layer and the outer layer rupture
25.7	8.4	5,701	Water leaks through holes in the outer rubber layer and the outer layer rupture
20.5	9.2	9,981	Water leaks through holes in the outer rubber layer
15.2	12.2	16,133	Water leaks through holes in the outer rubber layer and the outer layer rupture
9.2	19.3	54,548	Water leaks through holes in the outer rubber layer
4.3	29.8	156,065	Water leaks through holes in the outer rubber layer

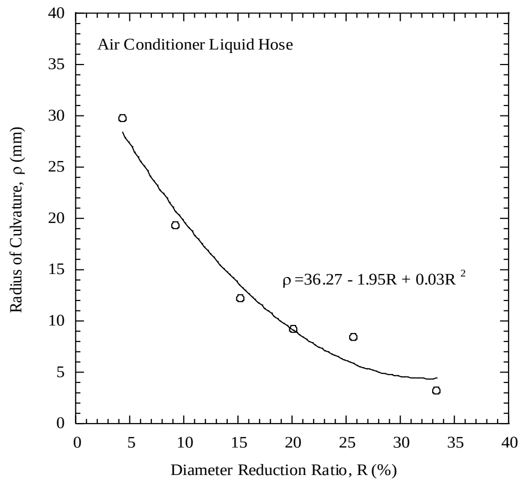


Fig. 7 Relationship between the radius of curvature and diameter reduction ratio of the liquid hose

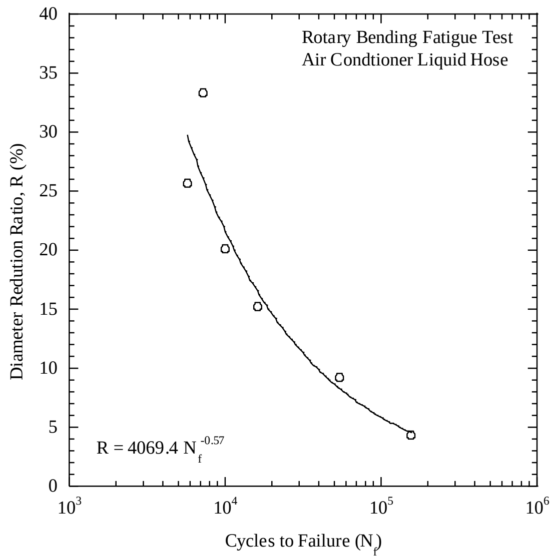


Fig. 8 Fatigue lifetimes as a function of the diameter reduction ratio of the liquid hose

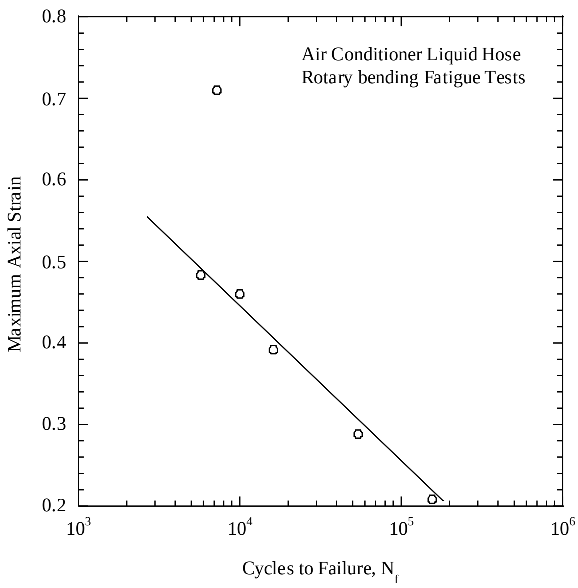
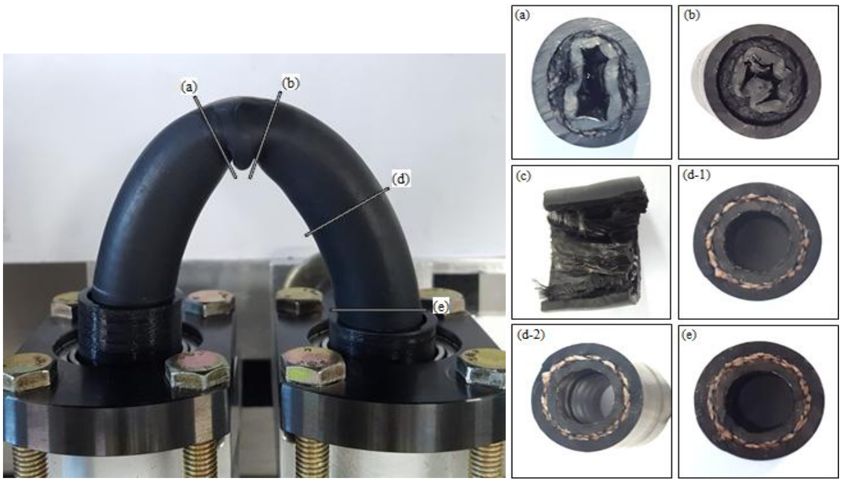


Fig. 9 Fatigue lifetimes as a function of the maximum axial strain of the liquid hose

Failure mode

In air conditioning liquid hose, fatigue damage occurred in two stages. The first stage involved damage to the inner rubber of the hose, which was subjected to tension and compression by repeated rotations, resulting in water leakage into the pinpricks machined in the outer rubber. The next stage involved outer rubber in the area where local buckling of the hose occurred due to continuous repeated rotations during which water leaked to the outer rubber area that subsequently ruptured.

The occurrence of the local buckling of the rubber hoses was mainly observed under test conditions with relatively large diameter reduction ratios when the hose was bent. Fig. 10 shows the shape of the specimen after fatigue testing with a diameter reduction ratio of 33.3% along with its cross-section. It was confirmed that severe local buckling occurred near the bent center of the test specimen. Fig. 10(a) shows the cutting position of the test specimen for investigating the cross-section of the tested hose. As shown in (a) and (b) of Fig. 10(b), the cross-sections of the region where local buckling occurred demonstrate that the inner rubber layer was excessively deformed and was separated from the reinforcing layer. In addition, (c) of Fig. 10(b) depicts a hose cut and unfolded between the cut areas in Fig. 10(b). Through this figure, it could be confirmed that the inner rubber and reinforcement layer were completely damaged. Additionally, (d-1) and (d-2) of Fig. 10(b) show the cross-sections of the middle of the region between the local buckling region, and the grip region, and (d-1) and (d-2) in Fig. 10(b) show the cross-section and inner layer of the region, respectively. Finally, (d-1) indicates that no significant deformation occurred at this position of the specimen. On the other hand, it was confirmed that the inner coating surface of the rubber was deformed into a wavy shape, as shown in (d-2) in Fig. 10(b). For (e) of Fig. 10(b), the section where a sleeve was mounted, and the inner and outer rubber and reinforcing layers were not significantly deformed or damaged.



(a) (b)

Fig. 10(a) Failed hose feature after the fatigue test with a diameter reduction ratio of 33% and (b) cross-section of each position of the hose in Fig. 10(a)

(a) (b)

Fig. 11 Hose feature (a) before and (b) after the fatigue test with a diameter reduction ratio of 25%

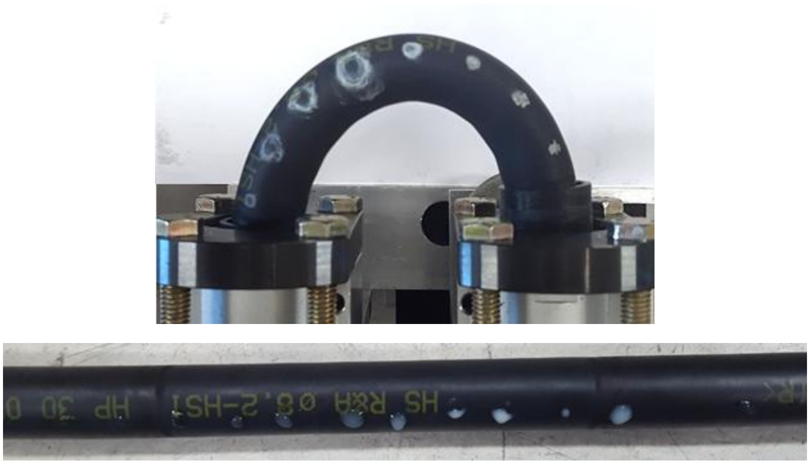


Fig. 12 Failed hose feature after the fatigue test with a diameter reduction ratio of 20%

Fig. 11 shows the shape before and after the fatigue test of the specimen with a diameter reduction ratio of 25%. Fig. 11(a) confirms that the hose center was folded into a certain shape prior to the start of the test, but no excessive local buckling occurred. On the other hand, Fig. 11(b) confirms that excessive local buckling occurred in the curved areas, similar to the specimen tested at an area reduction ratio of 33% with the shape after the fatigue test, as shown in Fig. 10(a). It was also confirmed that water leaked from pinpricks machined into outer layer rubber due to damage to the inner layer rubber and that water leaked from the folded part due to local buckling. Consequently, the occurrence of the local buckling of rubber hoses is thought to be due to repeated rotations of the inner layer rubber, resulting in excessive deformation of the inner layer rubber. The damage to the inner layer finally resulted in rupturing and leakage of the rubber hose.On the other hand, for the specimen tested with a diameter reduction ratio of 20%, relatively few cracks were observed in the inner layer rubber of the hose, which was subjected to tension and compression by repeated rotations, resulting in water leakage from pinpricks into the outer layer rubber. Fig. 12 shows the status of the failed fatigue specimen with a diameter reduction ratio of 20%. It was confirmed that water leaked from the pinpricks machined into the outer layer rubber of the area which underwent tensile and compressive stresses without damage to the reinforcement layer.

CONCLUSION

In this study, the relationship between the bending curvature radius of an air conditioning hose and the bending fatigue lifetime were determined through experiments. To this end, a testing device was developed and the fatigue damage mechanisms and durability of the hose were investigated. The results are as follows. The relationship between the maximum diameter reduction ratio (R) and the radius of curvature (ρ) of the hose was found to be expressed: $\rho = 36.27 - 1.95R + 0.03R^2$. Fatigue lifetimes were almost inversely proportional to the axial strain due to rotational loading except for a case with excessively reduced cross-sections by 33.3%. If the diameter reduction ratio was large, the inner rubber was excessively deformed in the cross-section of the area where local buckling occurred, the inner rubber and the reinforcing layer were completely destroyed, and leakage from the external rubber occurred. On the other hand, if the diameter reduction ratio was small, only a fracture of the hose's inner rubber was observed, resulting in water leakage from pinpricks on the outer rubber.

Acknowledgements

This study was financially supported by Seoul National University of Science & Technology.

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