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Fatigue Prediction of the Discharge Pipe in Reciprocating Compressor

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ABSTRACT

In this paper, a fatigue prediction of the reciprocating compressor was studied. The fatigue life of the LDT (Line Discharge Tube) situated in repeated load and the deformation was studied analytically and experimentally. Generally, there are two representative methods to predict the fatigue stress depending on the type of load. “Stress-Life scheme” can be applied to the problem which takes a lot of repeated stress within the elastic strain range. “Strain-Life scheme” can be used when it comes to the problem of low-cycle loading in the plastic strain range. In this paper, the Stress-Life scheme is used to predict fatigue life of LDT. Firstly, the analytical results verified using experimental method. Then, the relationships between design parameters and fatigue life were established using analytical model. Finally, the fatigue life design optimization of the LDT was progressed by means of the relationship.

1. INTRODUCTION

Fatigue stress analysis is generally performed using experimental stress or strain data. We have to handle too much data if use the measured load data as input of fatigue analysis. Even though the simply loaded case, the analysis is very difficult for implementing time domain load. In this case, analysis the applied load in the frequency domain then express that using PSD(Power Spectral Density) or express the system as a transfer function to predict the dynamic behavior of structures.

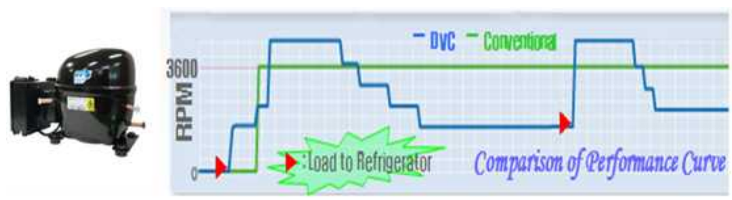


Figure 1 : Reciprocating compressor and driving speed

Fig.1 shows examples of operating mode of AC and BLDC reciprocating compressor. The BLDC compressor controls the rotating speed of compressor with respect to the thermal load of refrigerator. As a result, the Refrigerator with BLDC compressor shows high energy efficiency and small deviation of temperature. On the other hand, wide range of operating speed makes resonance problem of the compressor. So for BLDC compressor, it is essential design the components of compressor to avoid resonance vibration.

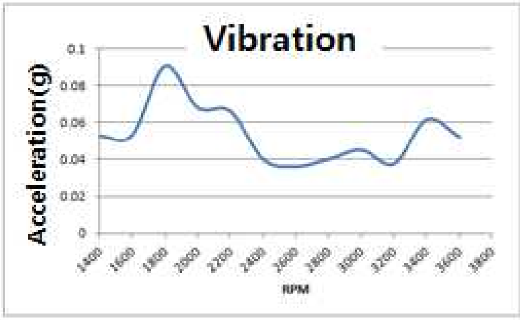


Figure 2 : Acceleration value of BLDC compressor

Fig.2 shows the vibration amplitude of a BLDC compressor with operating speed. As shown there are resonances at particular speeds, so the parts of the compressor include LDT must be designed to avoid these resonances. In addition when the compressor starts and stops, there is large deformation of LDT. In this paper the fatigue analysis of LDT is carried out and the results are compared with the experimental data.

2. Applying Fatigue Analysis

2.1 Overview of fatigue analysis

There are two kinds of fatigue analysis scheme depending on load types. "Stress-Life scheme" can be applied to the problem which takes a lot of repeated stress within the elastic strain range. "Strain-Life scheme" can be used for low-cycle loading within the plastic strain range. First of all, We have to choose the analysis scheme for LDT assembly by considering its loading condition.

As shown in Fig.3 the pump of the compressor is supported by suspension spring and LDT. So, the deformation of LDT is affected by the motion of pump. The maximum displacement is occurred when the compressor stops. And it is within the elastic strain range.

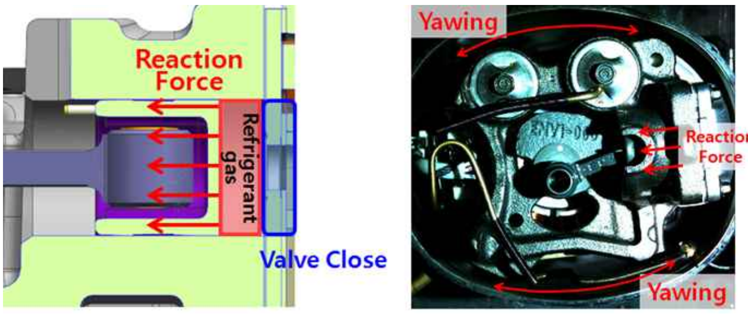


Figure 3 : Fatigue load occurring mechanism

2.2 The model validation of fatigue analysis

In advance to the fatigue analysis, identification of LDT assembly is obtained by analytically. And experimental validation is carried out.

LDT assembly is composed of 3 parts as shown in Fig. 4. Those are called Muffler Cover, Damping Spring and Tube.

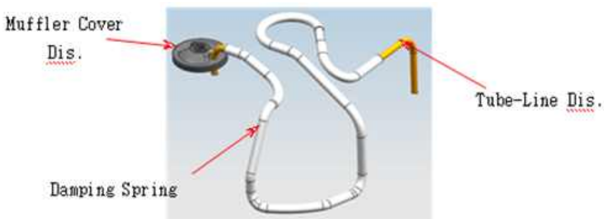


Figure 4 : Structure of LDT (Line Discharge Tube)

The damping spring is used to reduce the vibration of the tube using damping effect by frictional force. Frictional force generated between the damping spring and the tube, for fatigue analysis it is negligible. The density and elastic modulus of damping spring are calculated using material property superposition method. It is calculated using the mass and volume data. For the other two parts general steel material properties are used. (Muffler Cover - Cold rolled steel sheet, Tube - TDW (Tube Dual Wall)). Materials for analysis are shown in Table.1

a. Steel Tube (Shell Element : Φ4.0, T0.7)
ρ tube = 7.45X10-6 Kg/mm3
E tube = 2.08e+8 mN/mm3
b. Cover LDT (Shell Element : T2.7)
ρ cover = 7.23X10-6 Kg/mm3
E cover = 2.12e+8 mN/mm3
c. Damping Spring (Shell Element : Φ3.3, T0.7)
ρ damping = M tube + M damping / (V tube + V damping spring) = 9.08X10-6 Kg/mm3

Table 1 : Material properties of LDT

Modal analysis is performed using the basic geometry and material properties. Then the model integrity is processed by FRF test.

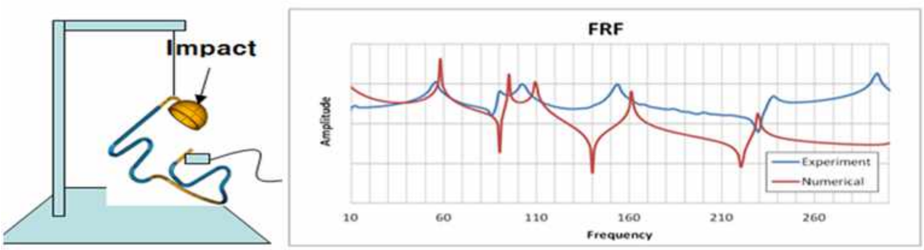


Figure 5 : FRF test

Mode	Discharge Pipe		
	Experiment	Numerical	Error
1	57	59	3.5%
2	90	95	5.6%
3	104	109	4.8%
4	229	238	3.9%

Table 2 : FRF results compare

Fig.5 shows the FRF test method and the result. Table.2 shows accuracy of the analysis model. The error of the 1st mode is 3.4% and the 2nd, 3rd modes are around 5% of error. It shows that material properties are appropriate and the accuracy of the analytical model is ensured. Material properties of table 2 are used for the fatigue analysis.

2.3 Experiment to find Load for fatigue analysis

Identification of the fatigue load is needed to find an input condition of analysis. For this purpose, the stop displacement was measured by using high speed camera. When the compressor is stopping, the fixed point of LDT is measured as the stop displacement.

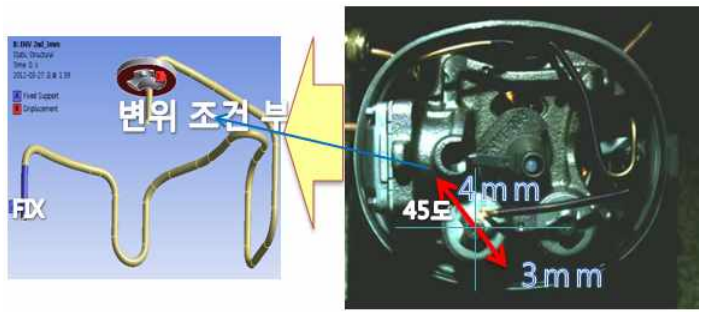


Figure 6 : Stop displacement of the LDT

The stop displacements were measured several times as shown in Fig.6. The stop displacements are considerably larger than driving displacements. Although the compressor is stopping the refrigerant is still remain in the cylinder. Remaining refrigerant compressed by the piston inertia. At this time pressure is developed in the cylinder. If the pressure is insufficient to open the discharge valve, it acts as a reaction force. This reaction force makes rotor rotate reversely. Stop displacement has the probability distributions depending on the stop positions of the piston.

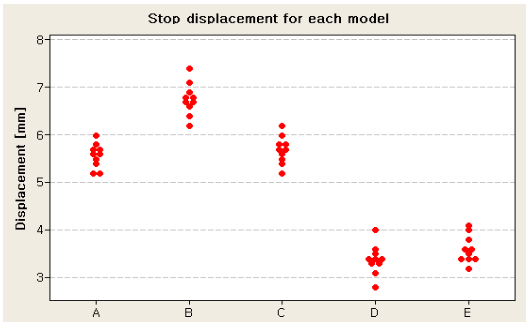


Figure 7 : Stop displacement of each Model

The stop displacement distributions of each model are different as shown in Fig.7. It is due to the difference of each model's cylinder displacement, the center of gravity, LDT shape and dimension.

In this paper, the maximum allowable fatigue stress of the LDT was calculated using the actual stop displacement.

The S-N curve is affected by the mean stress level. There are various methodologies to calculate the average stress. Typically, Soderberg, Goodman, Gerber theories are used. Among them Goodman theory is suitable for material fatigue analysis.

The understanding of S-N (Stress-Life) Curve is required to predict the fatigue fracture. Concept of S-N Curve is shown in Fig.8. Se is expression of Endurance limit. The trend curve can be obtained by experiment. It can be expressed as the following equation.

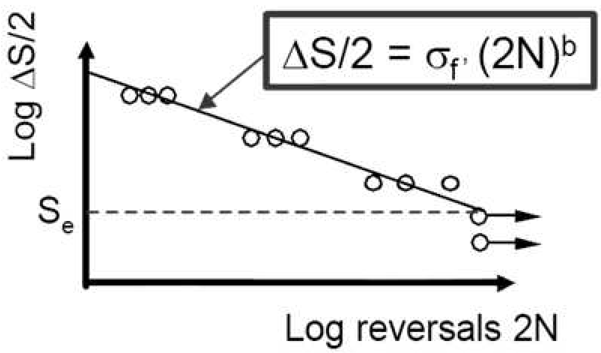


Figure 8 : S-N Curve

In the equation σ_f represents the fatigue strength coefficient and b is fatigue strength exponent. Typically b has a value between -0.12 and -0.05. The reliability test of the compressor is performed considering on warranty life of refrigerator. The components of the compressor have 3 to 4 times of safety factor.

In general, large amount of data are accumulated to identify the tendency of the fatigue fracture. Because, the fatigue fracture follow the probability distribution. For this paper, fatigue testing machine was designed and manufactured as shown in Fig.9. The analytical model is verified experimentally using this machine. Moreover experimental S-N curve was obtained as shown in Fig.10. A fatigue fracture is occurred when the amplitude of the stress above the S-N curve. The S-N Curve of the LDT is affected by design parameters such as material, outter diameter, thickness etc. So, each model's stress of amplitude and fatigue life is different. Fig.10 shows one of the measured S-N curves of LDT.

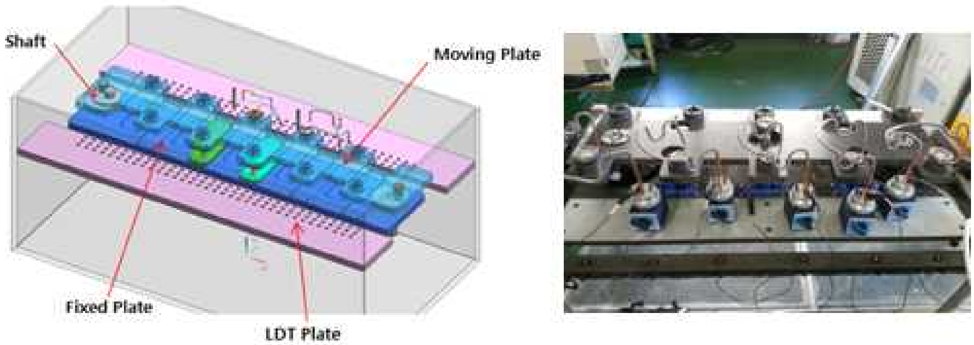


Figure 9 : Fatigue test machine

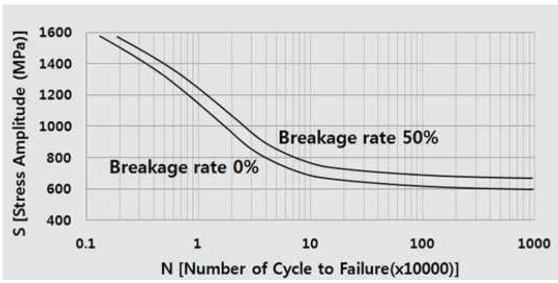


Figure 10 : S-N Curve of LDT

3. Fatigue life prediction results

3.1 Model and boundary condition setup.

The primary function of the LDT is transfer the compressed gas to the condenser unit. At the same time, it needed to minimize the flow loss caused by pulsation. In addition, LDT controls the posture of the pump. To analyze the fatigue life, LDT was modeled as shown in Fig.11. The model is divided into 3parts and meshes were generated as shown in Fig.11. The skewness of the parts is less than 0.7 for analysis.

The displacement data obtained from experiments were given to the analysis model using Goodman method as shown in Fig.12

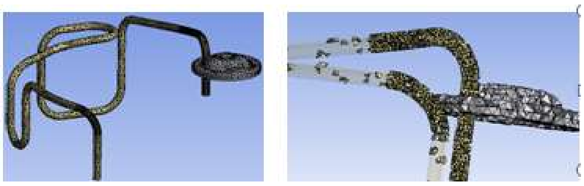


Figure 11 : Solid body of LDT

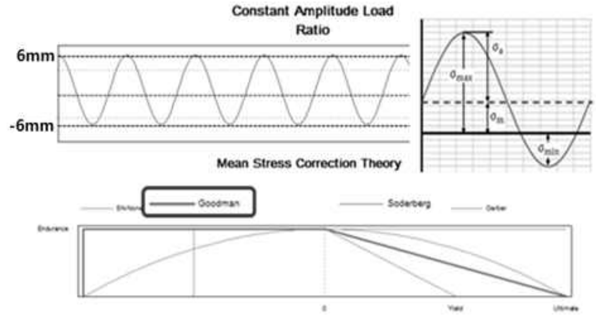


Figure 12 : Applying for stop displacement (Goodman)

The S-N curve from the experiment is inputted as shown in Fig.13.

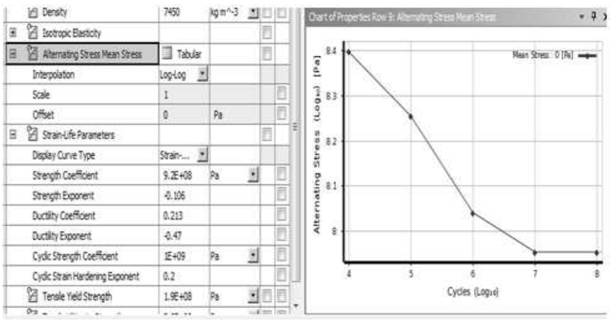


Figure 13 : Applying for stop displacement (Goodman)

3.2 Analysis method

To predict the LDT fatigue life the stress-life analysis method was used for a high-cycle load applied condition. The Constant Amplitude and Proportional Loading were used for stop displacement. Displacement loading was given using Goodman method. The result is analyzed by comparing the number of iteration fatigue load and fatigue failure location.

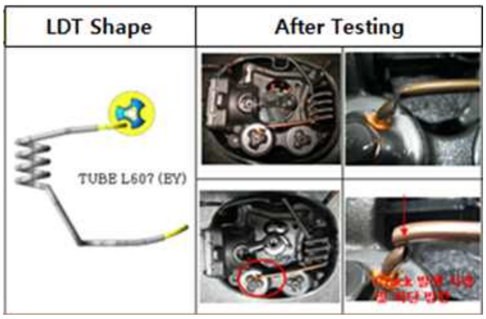


Figure 14 : Actual failure location of LDT

3.3 Analysis results and Model improvement

In the first analysis, the stress amplitude is 640MPa. it has around 2% of accuracy when comparing to experimental result. But the failure location is somewhat different from the experimental result. The accuracy of the analytical model was improved by model update process shown in Fig.14. Firstly, the welding condition is given at the stress concentrated position. And the sizes of mesh are adjusted. Through this process the accuracy of the analytical model was improved up to 70%. Finally, the accuracy of the analytical model was improved up to 87% by applying the experimental load. When considering the typical error rate of fatigue test (20%) the analytical model in this paper is well represents the real LDT.

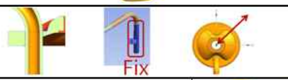
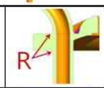
No.		ITEM		Stress [MPa	Comparison	
Experiment				640	100%	
Analysis	Basic				2%	
	1	- Add welding condition			20%	
	2	- Add welding condition - Fixed position change			70%	
	3	- Add welding condition - Fixed position change - Displacement change (Tabular data)			87%	

Figure 15 : Model Update

Based on this analytical model, we designed arbitrary shape of LDT then confirmed the fatigue failure problem. Experimental result shows that the intermittent failure occurs around 13k of load. The stop displacement of the pump is measured as shown in Fig.6. We found that 774Mpa of load is applied to the fracture. Applying this analysis result to the S-N curve the failure occurs approximately 11k. And it is around 15% of error. Finally, we can say that the arbitrary shaped Sample A has 10years of lifespan with 15% of error. This result shows that the component can cause a problem when considering safety factor. In this point of view several design improvements were suggested, and validated using analytical method. The results shown in Fig.16

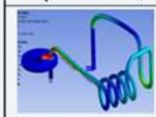
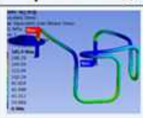
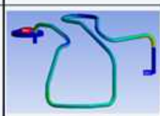
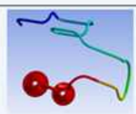
Model	A (Before Improvement)	A (After Improvement)	B	C
				
Stress [MPa]	774	695	668	254
Life cycle Prediction	113,872	758,159	1,225,186	1,495,772

Figure 16 : Analysis results each shape of LDT

Additionally, components related to fatigue must have permanent lift time. The component can be damaged at 10k or sometimes 100k if the design exceeds maximum stress. It doesn't achieve goal of lifetime. Therefore, components must be designed to have stress less than the maximum allowable stress.

4. Conclusion

In this paper, the analytical fatigue model of LDT was proposed. We made a LDT fatigue experiment system to validate this model. The proposed analytical model shows 15% of error compare to the experiment results. New LDT can be easily designed using this analytical model and validating process. As a result, designers can derive benefit of reliability cost saving and reducing development time for new LDT system design.

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