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Cumulative Damage Analysis for Hydraulic Hose Assemblies

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MATERIALS REPORT

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CUMULATIVE DAMAGE ANALYSIS FOR HYDRAULIC HOSE ASSEMBLIES

1. INTRODUCTION:

This report is intended to provide the hydraulic system analyst with a procedure which will assist in the selection and use of high-pressure wire reinforced hydraulic hose assemblies. Many construction, agricultural, industrial or commercial equipment systems utilize hydraulic hose assemblies that are subjected to irregular cyclic pressure variations (cannot be approximated by a constant amplitude pressure cycle). This SAE Information Report relates damage done by pressure cycles with the pressure-life performance curve for the hose assembly being evaluated, using a linear damage rule to predict fatigue life similar to that used for predicting metal fatigue life. More detailed information on the subject may be found in SAE Paper No. 880713 - SAE Test Program on Cummulative Damage for Hydraulic Hose Assemblies. The accuracy of cumulative damage calculations is directly related to proper measurement of the service pressure history and pressure-life performance for the hose assembly being evaluated. Final selection of a hose assembly must also consider installation and maintenance as noted in SAE J1273.

2. BACKGROUND:

In the current SAE J517 for hydraulic hose, each style and size hose is assigned a maximum operating pressure rating to assure the user reasonable service life in a wide variety of applications. (See Appendix A for further explanation of nomenclature used in this document.) This rating is based on assessment of many factors, including repeated pressure cycling under controlled laboratory conditions at a pressure equal to or greater than the assigned maximum operating pressure. This standard test procedure, as detailed in SAE J343 minimizes variables so as to provide a baseline for performance capability. SAE J517 takes note that actual pressure cycling in a hydraulic system will seldom duplicate those test parameters precisely. It

2. (Continued):

provides basic hose construction details; SAE J343 establishes standard test procedures - which may be utilized to develop data at pressures other than the established test value for any hose assembly. SAE J1273 provides a guide for selection, installation, and maintenance for hose and hose assemblies.

Many hydraulic systems will be subjected to variable amplitude pressure cycles, and in some of these the highest surge peaks will occur only a few times. Strict interpretation of SAE J517 indicates the use of hose with a maximum operating pressure equal to or greater than the highest peak - even if that peak should occur only once in the life of the system. If this were done, the hose would have more reinforcement, larger outside diameter, less flexibility, and higher cost than might be needed. It should not be necessary to use a hose that has over a million cycle capability at a pressure which is likely to occur only a few times in the application. What is needed, then, is a design verification procedure that assures adequate fatigue life for applications with variable amplitude pressure usage where the majority of the peaks are between 100 and 200% of rated pressure.

2.1 Cumulative damage of hydraulic hose is in many ways comparable to cumulative damage of metal components. The design verification of metal components is done in two ways depending on whether loading is of constant amplitude or variable amplitude:

a. Size the part cross section so the constant amplitude (maximum) load will not produce a stress at the highest stressed area in excess of the material "endurance limit stress." This is a stress that will not cause failure in a million cycles of loading.

b. Do a cumulative damage analysis on the variable amplitude load or strain history to predict fatigue life as is normally done to evaluate prototype machines in the ground vehicle industry.

2.2 In a similar manner, hydraulic hose design verification should be done in two ways:

a. Select a hose assembly so the constant amplitude (maximum) pressure during service is less than the SAE J517 rated pressure.

b. Do a cumulative damage analysis with the variable amplitude pressure history to determine if the fatigue life will meet the design life of the product. The block diagram in Fig. 1 illustrates how both the pressure history and the P-N curve information are the essential inputs for this procedure.

For both metal parts and hydraulic hose assemblies, the first method is appropriate when the load (pressure) is known to be a large number of cyclic applications of nearly constant amplitude. However, if the load (pressure) involves infrequent cycling or includes only a few large peaks, then the first method may lead to designs that are heavy, bulky, inflexible, and more costly than need be. For variable amplitude loads or pressure applications, it is logical to do a cumulative damage analysis to judge the adequacy of the design.

2.2 (Continued):

Other factors, such as internal temperature, ambient temperature, and ozone exposure, for all intents and purposes, have not been considered in this cumulative damage analysis procedure. Long-term exposure to extreme limits or high levels of these elements could affect the overall hose assembly life.

3. USE OF P-N CURVES IN DESIGN:

A cumulative damage analysis is needed for a hydraulic system subjected to variable amplitude pressure cycles if system pressures in excess of rated pressure are to be in the design consideration. An approach for this analysis is to use the Reference P-N curve as defined in the previously mentioned reference paper and shown in Fig. 2. Verification that the actual hose assemblies have a P-N curve in excess of the Reference P-N curve is essential. The equation for the Reference P-N curve in Fig. 2 is:

$$P_a = P_b(N)^s \qquad \text{Eq. (1)}$$

where: P_a = Zero-to-Max amplitude of pressure cycle
N = Cycles to failure at pressure amplitude P_a
P_b = Burst pressure (one cycle life)
s = Slope of curve on log-log plot

By using two known points on this line:

- 1 cycle at 400% (Burst Point)
- 200 000 cycles at 133% (Impulse Point)

the values of P_b and s can be found:

$$P_b = 400 \text{ and } s = -0.0902$$

and:

$$P_a = 400(N)^{-0.0902} \qquad \text{Eq. (2)}$$

Rearranged to a more useful form to solve for N cycles at any pressure P_a this becomes:

$$N = \left[\frac{400}{P_a}\right]^{11.086} \qquad \text{Eq. (3)}$$

If a different impulse point (for example 500 000 cycles at 133%) were used, this would result in a different slope for the P-N curve. The Hydraulic Design Analyst has the option of using other Reference P-N curves in the analysis as long as there are data to demonstrate the actual P-N curve is in excess of the Reference P-N curve. In addition, the analyst can increase statistical confidence by requiring a low percentage failure P-N curve (for example, a B_{10} Curve) for test data for the hose assembly being considered to be in excess of the Reference P-N curve used in the analysis. (This is explained in greater detail in SAE Paper No. 880713.)

3. (Continued):

In order to use this prediction procedure, a sample pressure history has to be available. The cycle counting procedure for a pressure history is explained in more detail in the next section. The fundamental theory for damage accumulation uses zero-to-max pressure cycles since the P-N curve is determined from zero-to-max test pressure cycles. This is slightly different than for stress-life or strain-life curves for metal where there are fully reversed loads (zero mean stress). It is appropriate to resolve pressure cycles to zero-to-max cycles (mean pressure equals one-half of the maximum) since any possible negative pressure must be very small compared to the "high pressures" generally used in wire reinforced hydraulic hose assemblies. The damage is accumulated in a linear manner as is done for metal fatigue:

$$D = \sum_{i=1}^{j} \frac{n_i}{N_i} \qquad \text{Eq. (4)}$$

where: D = Damage done (D = 1 assumes failure)
n_i = Number of cycles in the history at amplitude i
N_i = Number of cycles to cause failure at amplitude i
j = Number of different amplitudes in the history

This equation and the P-N curve illustrates that when subjected to repeated constant amplitude pressure cycles above a given level, a hose assembly will eventually fail. The higher this constant amplitude pressure, the shorter the life. If the pressure is large enough, then failure can occur in one cycle. This is a burst test and is represented by the one cycle pressure value at the left end of the P-N curve and is analogous to the ultimate strength of metal parts. Damage due to a variable amplitude pressure history (which has been resolved to zero-to-max cycles) is then simply the sum of the n_i/N_i for all the different amplitudes in the history. When this summation equals one, failure is predicted.

If a typical pressure history of a given length of time (t) (time factor is machine operation time, not calendar time) is analyzed, Equation 4 will give a decimal fraction for the damage done. Then the fatigue life prediction is:

$$\text{Life(L)} = t(1/D) \qquad \text{Eq. (5)}$$

For example, if D = 0.01, one one-hundredth of damage has been done in t units of time and the total expected life would be one hundred times t units of time for the total life.

The procedure will work with either constant or variable amplitude pressure histories. Fig. 1 illustrates how the P-N curve and the pressure history are the two necessary inputs for the procedure. If the user of the procedure has test data to demonstrate that the actual P-N curve is in excess of the reference P-N curve, then life predictions will be conservative for the sample pressure history that is used in the analysis.

4. PRESSURE HISTORY CYCLE COUNTING:

Typical hydraulic hose pressure histories are variable amplitude and are almost totally positive pressure. Depending on the hydraulic component that the hose may be connected to, it is sometimes possible to have a partial vacuum in a hose. In the worst possible case, this could never be more than one atmosphere, which is small compared to the maximum that "high pressure" hoses normally experience, but should be avoided in system design as the impact on useful life is far greater than a numerical relationship would suggest. For cycle counting, pressure cycle histories will be considered to be all positive pressures. As indicated in the previous section, the cycle counting procedure needs to be designed to resolve the pressure history into zero-to-maximum pressure cycles since this is the type of pressure cycle used to determine the P-N curves.

A cycle counting procedure is discussed in detail in SAE Paper No. 880713 and suggests the following three steps:

a. Tabulate the pressure peaks from the history and assume each is followed by a minimum pressure value of zero.

b. A pressure peak is defined as a maximum value that is preceded and followed by pressure minimums of a specified lower magnitude (threshold). A pressure maximum that does not meet this requirement is not counted.

c. Threshold must be selected based on engineering judgment of the analyst.

As a result of the above steps, all cycles that are counted will be zero-to-max cycles and can be used directly in the damage Equation 4. The threshold value needs to be at least 35 to 50% of the hose rated pressure to avoid counting cycles that are small pressure undulations and not pressure cycles that cause significant fatigue damage. Engineering judgment must be used to select the threshold to make an appropriate cycle count. This cycle counting procedure assumes the pressure minimums following significant maximums are zero. This was done to keep the procedure simple, practical, and conservative but not ultraconservative when only a few large pressure cycles are in the history. If, however, the service history does have a large number of cycles at the largest value, this evaluation procedure will still give the appropriate cycle count and life prediction. It will work with constant amplitude histories just as well as with variable amplitude histories.

An important part of the cycle counting is the ability to determine when a maximum should be kept as a peak. Fig. 3 shows the four possible cases that can occur. Only case one is considered a valid peak and kept for the cycle counting. From Fig. 3:

4. (Continued):

Case I

$R_1 > T$ and $R_2 > T$
Count P_1

Case II

$R_1 > T$ and $R_2 \leq T$
Discard P_1 and V2
Keep V_1 as Valley
Consider next Peak and Valley

Case III

$R_1 \leq T$ and $R_2 > T$
Discard P_1 and V_1
Keep V_2 as Valley
Consider next Peak and Valley

Case IV

$R_1 \leq T$ and $R_2 \leq T$
Discard P_1 and highest Valley
Keep lower Valley
Consider next Peak and Valley

5. SUMMARY OF PROCEDURE TO PREDICT HOSE ASSEMBLY LIFE:

5.1 The analyst must have data to demonstrate that the actual P-N curve for the hose assembly under consideration falls above and to the right of the Reference P-N curve.

$$P_a = P_b(N)^S \qquad \text{Eq. (1)}$$

For a burst of 400% of rated pressure and a 200 000 cycle life at 133% of rated pressure this is:

$$P_a = 400(N)^{-0.0902} \text{ rearranged } N = \left[\frac{400}{P_a}\right]^{11.086} \qquad \text{Eq. (2,3)}$$

5.2 Establish a sample pressure history for the system for a known time.

5.3 Determine valid "peaks" and count the number of occurrences (n_i) for each peak value (amplitude) in the sample pressure history.

5.4 For each peak value, calculate cycles to failure (N_i) from the Reference P-N curve (step 5.1).

5.5 For each peak value, calculate the ratio of counted cycles (n_i) and the projected number to failure (N_i) to determine the fraction of damage for each peak value.

5.6 Total all fractions of damage from (step 5.5) for total damage (D) due to the sample pressure history.

5.7 Project the fatigue life (L) as the ratio of system operation time (t) for the sample pressure history divided by the total of all damage incurred during that time.

$$L = t(1/D) \quad \text{Eq. (5)}$$

6. SAMPLE PROBLEM FOR CUMULATIVE DAMAGE:

This simple example is used to illustrate the complete cumulative damage procedure. It shows how to cycle count a sample pressure history, see Fig. 4, and then calculate the damage done and predict the life of the hose for the sample pressure history. The example is done "by hand" since it is only a few peaks and valleys. "Real" histories would be much longer and would logically be done with a computer program that has been programmed to consider the various special cases of cycle counting and choice of threshold.

Tabulate original maximum-minimum sequence as potential peaks and valleys.

V-P-V-P-V-.....P-V

Note history is assumed to start and end with a valley of zero.

a	b	c	d	e	f	g	h	i	j	k	l
0	120	40	140	120	150	50	160	100	110	30	180

m	n	o	p	q	r	s	t	u	v	w	x	y
70	130	110	170	40	80	20	110	90	110	40	150	0

Follow procedure in the previous section and Fig. 3 to determine which potential peaks will be counted.

For this example assume threshold is 35%.

Counted peaks which result are:

b	f	h	l	p	r	t	x
120	150	160	180	170	80	110	150

Then for a hose assembly that has a P-N curve in excess of Reference P-N curve, use Equation (3) to calculate N_i for each P_a. Table 1 shows the tabulated results for the sample pressure history.

Using Equation (4)

$$\Sigma n_i/N_i = 29.8 \times 10^{-5}$$

Assume pressure history is for 0.5 hours. Then from Equation (5)

$$\text{Life}(L) = \frac{0.5}{29.8 \times 10^{-5}} = 1679 \text{ hours}$$

APPENDIX A

1. NOMENCLATURE:

To facilitate understanding of the concept and life calculation procedure used in this document and in related documents, the following nomenclature is used.

2. PRESSURE HISTORY:

The time oriented variations of internal pressure in a hydraulic system (hose assembly). This may be tabulated by listing a sequence of relative maximums and minimums from recorded pressure vs. time data. Significant maximums and minimums are called peaks and valleys. (See section on cycle counting.) A peak is defined as a maximum both preceded and followed by a minimum less than the peak by a specified amount or threshold (differential pressure). A valley is defined as the smallest minimum between significant peaks. Note that it is possible for peaks to be lower than valleys in cases where they are not adjacent. Likewise, valleys could be greater than non-adjacent peaks.

3. THRESHOLD (DIFFERENTIAL PRESSURE):

The magnitude of pressure difference (differential pressure) between a maximum and adjacent minimum in a pressure history that is considered significant by the hydraulic design analyst. This threshold (differential pressure) must be chosen by the analyst and is usually at least 35% of the hose rated pressure. If both the differential pressure before and after a maximum are equal to or greater than the threshold, then that maximum is defined to be a significant peak in the pressure history. (See Fig. 3.)

4. SAMPLE PRESSURE HISTORY:

A representative recording for a given length of time of the pressure history for a hydraulic hose. Generally, a sequence of peaks and valleys for a given length of time, requiring a choice of threshold to disregard insignificant pressure variations.

5. CONSTANT AMPLITUDE PRESSURE HISTORY:

A pressure history where all the peaks are of similar magnitude with the valleys near zero.

6. VARIABLE AMPLITUDE PRESSURE HISTORY:

A pressure history where the peaks and valleys are irregular.

7. RATED PRESSURE:

The reference pressure or "nominal design pressure" for a hose assembly from which other pressures are based.

8. OPERATING PRESSURE:

(Used in SAE J517) Same as rated pressure.

9. MAXIMUM OPERATING PRESSURE:

(Used in SAE J517) Same as rated pressure.

10. MINIMUM BURST PRESSURE:

Defined as 400% of rated pressure.

11. BURST PRESSURE:

The actual pressure at which a hose assembly fails when subjected to slowly increasing hydrostatic pressure (see SAE J343).

12. SURGE PRESSURE:

(Used in SAE J517 and J1273). A rapid and transient rise in pressure in a pressure history.

13. IMPULSE TEST PRESSURE:

A laboratory test pressure level to which a hose assembly is repeatedly subjected with near zero valleys between peaks. (See SAE J343.) Generally given in percent of rated pressure and is usually greater than 100%.

14. IMPULSE LIFE:

The number of cycles to failure for a hose assembly when subjected to cyclic testing for a given impulse test pressure.

15. FATIGUE LIFE:

The predicted time to failure (length of operational service) for a hose assembly in a working hydraulic system, based on a sample pressure history and cumulative damage calculations.

16. CUMULATIVE DAMAGE CALCULATION:

A procedure to calculate fatigue life of a hose assembly by relating pressure cycles and fatigue damage for a sample pressure history with a given P-N curve.

17. PRESSURE-LIFE (P-N) CURVE:

The relationship between impulse test pressure, P, and impulse life, N, for a given type and size of hose. Can be plotted as a line on a log-log chart of percent of rated pressure and cycles to failure.

18. REFERENCE P-N CURVE:

A straight line relation on a P-N plot connecting one cycle at 400% (minimum burst) with the impulse test point (for example 200 000 cycles at 133%). In this form (percent of rated pressure vs. life), hoses with different rated pressure all plot with the same Reference P-N curve. P-N curves can also be plotted with pressure units rather than percent of rated pressure. In this form, a "family" of parallel P-N curves result for different rated pressures.

19. 10% P-N CURVE-B_{10} CURVE:

A P-N curve for test data where 10% failure of a population of hoses would occur. Can be used to increase the statistical confidence of life prediction (see reference paper #880713).

TABLE 1 - Tabulated Data

PRESSURE AS A % OF RATED PRESSURE	CALCULATED CYCLES TO CAUSE FAILURE @ PRESSURE i	COUNTED CYCLES IN HISTORY @ PRESSURE i	DEGREE OF DAMAGE EFFECTED BY n_i
P_a	N_i	n_i	n_i/N_i
80	56 x 10^6	1	0.178 x 10^{-7}
110	16.4 x 10^5	1	6.09 x 10^{-7}
120	62.6 x 10^4	1	16.0 x 10^{-7}
150	52.8 x 10^3	2	3.79 x 10^{-5}
160	25.8 x 10^3	1	3.87 x 10^{-5}
170	13.2 x 10^3	1	7.59 x 10^{-5}
180	6.99 x 10^3	1	14.3 x 10^{-5}