CHAPTER 42
LOAD-CYCLE ANALYSIS

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GLOSSARY OF SYMBOLS

A	Area
F	Force or load
N	Normal force, speed
p	Pressure
Q	Flow rate
t	Time
T	Torque
v	Velocity
$\dot{\theta}$	Angular velocity
μ	Coefficient of friction
ω	Angular velocity

42.1 INTRODUCTION

This chapter deals with the technologies of basic *energy transmission systems* as used by product- and process-oriented industries and the military establishment. Figure 42.1 and Table 42.1 illustrate the essence of these types of systems.

These classes of energy transmission systems can be characterized as follows:

I. Mechanical rotary input in the form of
- **A.** An input speed N_i which can be constant or variable
- **B.** An input torque T_i which is variable, responding to the instantaneous demand of the energy transmission system, i.e., the output impedance of the prime mover

FIGURE 42.1 The energy transmission system is an interface between an input element such as a prime mover and an output element such as a load. The dashed lines indicate interfaces. *(From Ref. [42.1].)*

TABLE 42.1 Various Energy Transfer Systems as Interfaces between Input and Output

Input or source	Energy transmission system	Output or load
AC electric motors DC electric motors Spark-ignition internal-combustion engines Diesel engines Gas turbines Steam turbines Air motors Water motors	1. Electric systems 2. Mechanical systems 3. Fluid power systems	Linear output v_0, F_0 Rotary output N_0, T_0

SOURCE: Ref. [42.1].

II. Mechanical output in two basic forms:
- **A.** Linear
  1. An output linear velocity v_0 or $\dot{x}$ which can be constant or variable
  2. An output force reaction F_0 which can be constant or variable, responding to the instantaneous changes in load reaction, i.e., the output impedance of the actuator
- **B.** Rotary
  1. Limited-rotation actuators
     - *a.* An output *rotational* velocity ω or $\dot{\theta}$ which can be constant N_0 or variable $\dot{\theta}$
     - *b.* An output torque reaction T_0 which can be constant or variable, responding to load changes
  2. Continuous-rotation motors
     - *a.* An output angular velocity which can be constant N_0 (usually as speed N instead of ω_0) or variable $\dot{\theta}$
     - *b.* An output reaction torque T_0 which can be constant or variable, responding to load changes

In Fig. 42.1 the energy transmission system is an *interface* between an *input* (prime mover) and an *output* (load). The energy transmission system must next be broken down into its *functional sections,* as shown in the block diagram of Fig. 42.2.

42.1.1 Functional Segments

An energy transmission system has three functional sections:

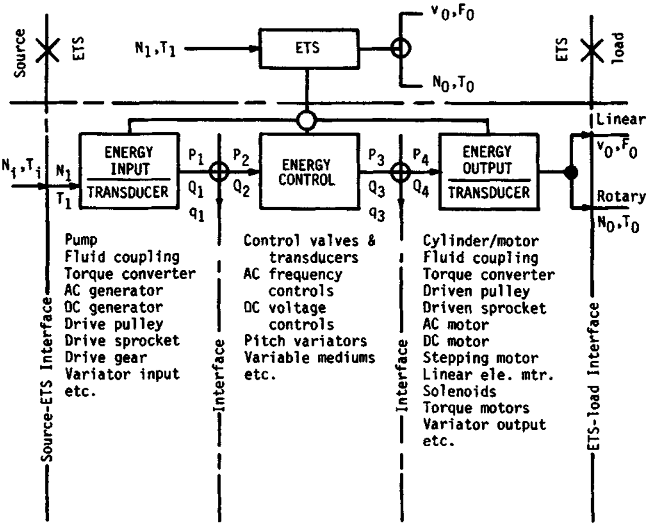

FIGURE 42.2 Block diagram of typical energy transmission system subdivided into its three major categories. *(From Ref. [42.1].)*

I. *Energy input devices* receive the energy from the prime mover across the *source-energy transmission system* interface.
- **A.** The input variables are the input speed N_i and the input torque T_i.
- **B.** The output variables are represented by pressure p_1 and flow Q_1.
- **C.** Typical examples of energy input devices are shown in Fig. 42.2.

II. *Energy output devices* receive the energy transmitted by the energy transmission system, transduce it to mechanical output, and deliver it across the energy transmission system-load interface to the *load.*
- **A.** Input variables to the energy output devices are p_4 and Q_4.
- **B.** Output variables from the energy output devices are
  1. Linear output v_0 and F_0.
  2. Rotary output N_0 and T_0.
- **C.** Typical examples of energy output devices are shown in Fig. 42.2. Commercially there is a wider variety of available energy output devices than of energy input devices.

III. *Energy control devices* receive energy from the energy input devices in the form of input variables p_2 and Q_2. Energy control devices modulate the energy as they transmit it and deliver it in the form of output variables p_3 and Q_3. Note that the intersectional interfaces are shown within the energy transmission systems.
- **A.** There is an interface between the energy input devices and energy control devices section.
- **B.** There is an interface between the energy control devices and the energy output devices section of the overall energy transmission system.
- **C.** Intersectional energy losses (i.e., transmission losses), symbolized by q_e, are shown lumped at a summing point located at the internal interfaces.

There is a fourth section to a fluid power energy transmission system: the *auxiliaries*. This section consists of all the components needed to implement a practical system. However, these components participate in neither energy transfer nor control. Typically they are piping, fittings, hoses, reservoirs, fluid, and filters.

The next step is to consider the relationship of the control function to the other sections of the overall system (see Fig. 42.3).

Most control situations are a combination of two or more of these three basic functions. The term *control* tells how these three control functions relate to the other sections of the total energy transmission system.

42.2 LOAD-DOMINATED ENERGY TRANSMISSION SYSTEM

One more factor must be considered before the designer can approach the subject of fluid power circuit design effectively, namely, the *load-oriented* nature of the kinds of energy transmission systems previously defined. The fact that these systems are *load-dominated* is illustrated in Fig. 42.4, which uses a single hydraulic energy transmission system as the example.

The block diagram in Fig. 42.4 is that of Fig. 42.2. Below the functional representation is a schematic, using International Organization for Standardization (ISO) graphic symbols (see Ref. [42.2]) of the hydraulic system consisting of one pump, one control valve, and either a linear actuator or a continuous-rotation hydraulic motor. The curves below the schematic illustrate the key point: the load domination of the system.

Hydraulic systems, which ordinarily use positive-displacement input-output devices such as pumps, actuators, and motors, transfer energy by means of *potential energy changes in the fluid transfer medium,* that is, by virtue of hydrostatic fluid pressure level differentials Δp. The rate at which the energy is transferred is a function of the flow Q. These two variables—pressure and flow—are essentially independent of each other.

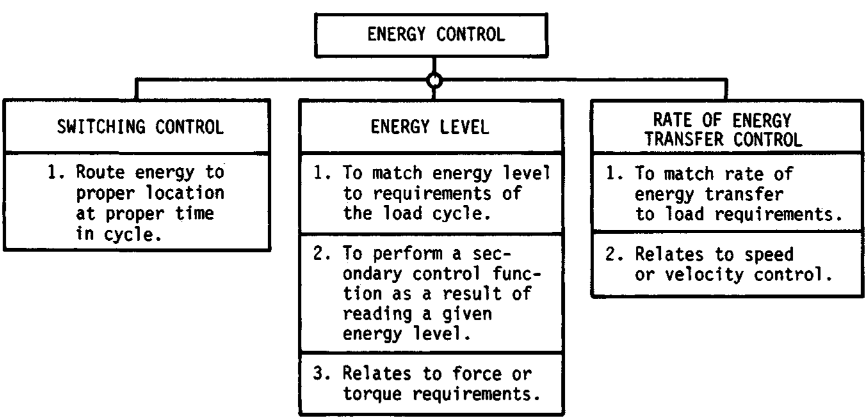

FIGURE 42.3 Block diagram to illustrate the relationship of the control functions to other sections of the overall system. *(From Ref. [42.1].)*

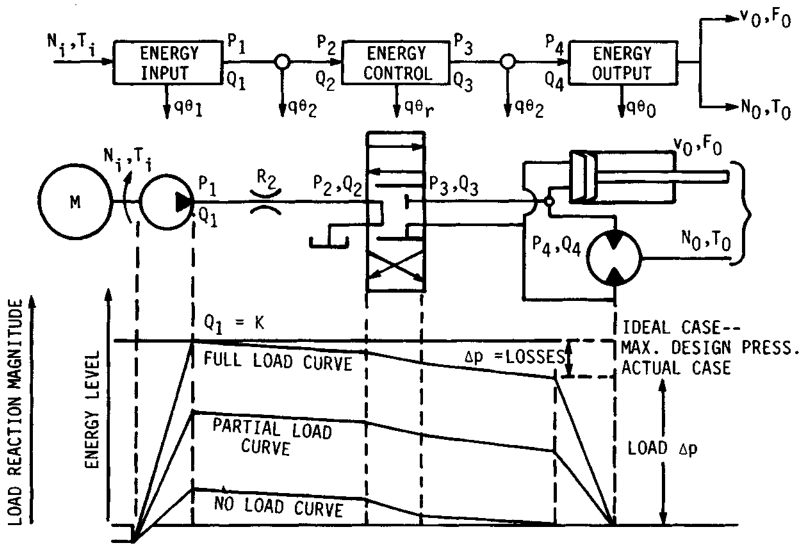

FIGURE 42.4 This diagram illustrates the load-oriented nature of energy transmission systems. *(From Ref. [42.1].)*

There is a common misconception concerning fluid power systems—that the pump generates pressure in the fluid transfer medium. It does not. A positive-displacement pump transfers fluid into a system at a controllable rate *against* an impedance, namely, some resistance to fluid flow. A small part of the resistance emanates from the piping, hoses, fittings, orifices, and other restrictions in the fluid-conducting components. Energy losses due to this part of flow resistance show up as pressure drops—and account for the downward slope of the energy-level curves in Fig. 42.4. The shapes of these curves remain the same for any constant flow in any given system, regardless of overall pressure level. By far the greatest part of resistance to fluid flow comes from the load itself. Pressure (Ref. [42.3], pp. 5–9, 27) is an indication of the potential energy level of the fluid caused by load reaction distributed across the actuator interface area. As load reaction varies, pressure varies accordingly.

As illustrated in Fig. 42.4, when the load reaction is varied, the load curve shifts up and down between the no-load level, representing the summation of pressure differentials $\Sigma\Delta p$ only around the circuit, and the maximum load curve, representing the upper load reaction limit for which the system was designed for safe operation.

Other types of potential energy level transfer systems would exhibit analogous characteristics. Although kinetic energy transfer systems would show different characteristics, the concept would be similar.

42.3 MACHINE-CYCLE ANALYSIS

A complete, quantitative analysis of the machine under consideration is the first requisite for effective fluid power circuit design. It is common practice to use steady-state load analysis in designing open-loop circuits and dynamic load analysis in designing closed-loop systems.

The cycle profile† is the recommended technique for displaying the results of machine-cycle-load analysis.

42.3.1 Case Study—Machine-Cycle Analysis

The following case study illustrates the total approach to a practical circuit design problem, the hydraulic excavator, an actual example from industry.

The first step is to analyze the machine cycle. This analysis turns out to be a time-and-motion study of the operation of the machine. If an actual study is not available to the designer, she or he must make up an estimated cycle.

A flow diagram, like that shown in Fig. 42.5, is a valuable preliminary. In this case, two possible work cycles are admitted to the analysis. Cycle 1 applies when the excavator is to load into a dump truck. Cycle 2 applies when the excavated material is to be spread on the ground within reach of the bucket. The events listed in the left-hand side of the flow diagram describe the actions to be completed at each stage of the cycle. When the diagram has been completed, it provides a visual reference for a step-by-step progression through the work cycle. With such a tool at one's disposal, it is very difficult to make a serious error in the cycle plot.

† Cycle profile technique is discussed in detail in Ref. [42.1], pp. 16, 26, 29, 40, 41, 249, 348.

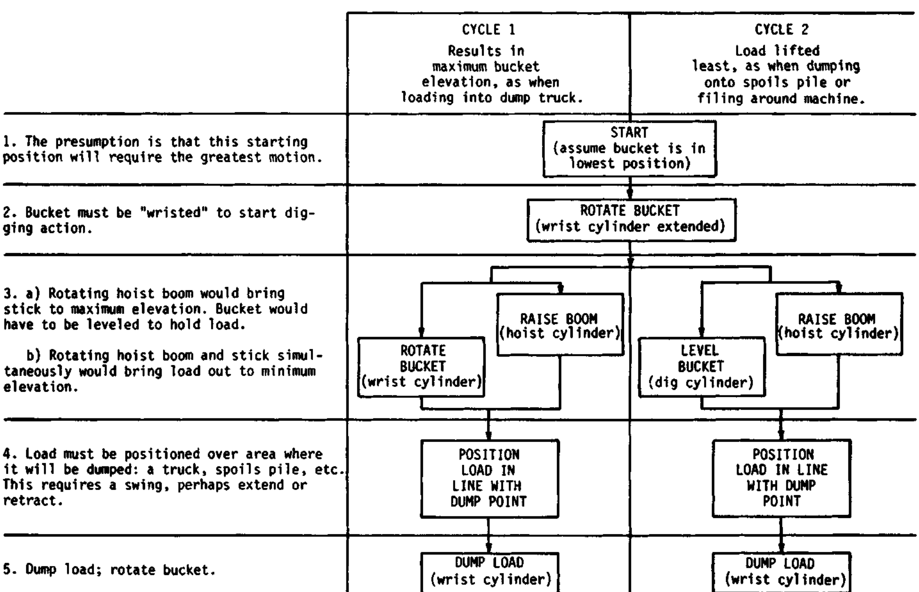

FIGURE 42.5 Flow diagram of the work cycle for a hydraulic excavator. The flow diagram shows primary action only. It is understood that adjustments may be necessary which would necessitate simultaneous operation of the actuators. *(From Ref. [42.1].)*

The next step is to draw a cycle-sequence plot like that shown in Fig. 42.6. The diagrams of machine operations across the top of the sequence plot simplify the communication problem when one is trying to convey the meaning of the plot to persons other than the design group. Each actuator on the machine has been assigned a code letter, from *A* to *J*. These code letters are listed along the left edge of the sequence plot in their order of actuation in the work cycle. The length of the horizontal bar in the diagram indicates the length of time the particular actuator is on. Overlapping of bars indicates that two or more actuators are operating simultaneously. This is an example of how an important point can be brought out graphically by making a sequence plot—in this case, simultaneous operation of motors. It is very difficult to pick up all such instances of overlapping in an intuitive analysis of a circuit.

Now start the load plot, which is the first step in drawing the cycle profile.

42.4 LOAD PLOTS

A separate load plot is required for each actuator in the circuit and for each motion in the cycle.

To better understand the function of a cylinder and its effect on loading, consider the load conditions which occur during a single extension stroke of a cylinder. The question is: What load? General practice has been to work on the basis of the maximum load, either calculated or estimated by the designer. If the engineer is fortunate enough to have an operating system at his or her disposal, a pressure transducer can be used to "look at" the pressure transients that occur as the cylinder is started up and extended. The engineer would see a pressure peak occurring over a short time. This phenomenon is called *breakaway* (Ref. [42.1], pp. 14, 36, 104, 136, 137).

In the time increment $0 < t < dt$, the cylinder must overcome a friction load resistance due to static friction of the total system; this includes external and internal friction. It must also overcome any residual external load applied to the system, for instance, the weight of the arm and bucket, plus any material in the bucket, on the

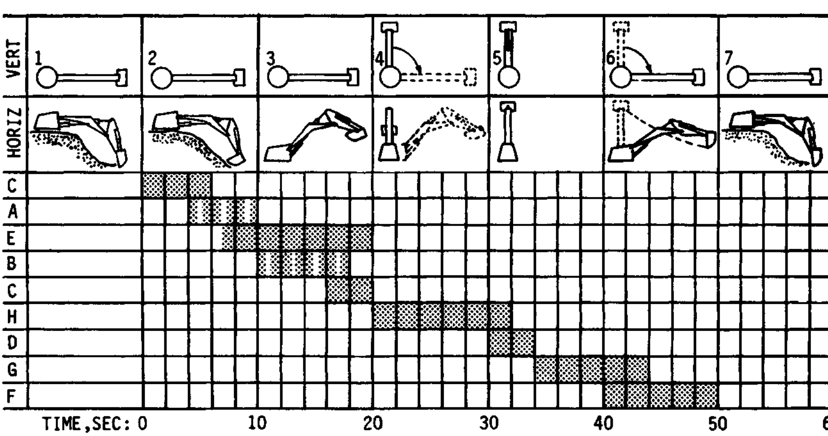

FIGURE 42.6 Cycle-sequence plot. Method 1: maximum bucket elevation. Actuator sequence code is: *A*, extend dig-cylinder rod; *B*, retract dig cylinder; *C*, extend wrist-cylinder rod; *D*, retract wrist cylinder; *E*, extend hoist-cylinder rod; *F*, retract hoist cylinder; *G*, swing clockwise; *H*, swing counterclockwise; *I*, traction forward; *J*, traction reverse. *(From Ref. [42.1].)*

excavator. Note that we have not yet considered acceleration forces, because in time dt the system has not yet started to move. One might say that, so far, the cylinder has simply been taking up the lost motion, or backlash, in the system.

This brings up a fine philosophical point not often recognized. Capacitance in a system, which is due to compressibility of the fluid, compliance, and slip in components, is generally regarded as a negative quantity, that is, one that detracts from the performance of a fluid power system. The consensus seems to be that if capacitance were eliminated, then the system efficiency would be optimized. But consider the following: If the system is at zero velocity at $t = dt$, and if it is accelerated to some velocity v_1 in an infinitesimally small increment of time $+dt$, then as $+dt - dt$ approaches 0, it is necessary for the system to accelerate from zero velocity to some finite velocity in zero time. This would require an infinite acceleration. However, the fact that there is capacitance in the system allows us to transfer energy to the fluid in a finite time interval, thus eliminating the requirement for infinite acceleration. It is quite possible that a fluid power system could not be started if the fluid and the system were perfectly inelastic.

In a practical system, of course, the relief valve also enters into the picture, since it will "crack" and bypass excess fluid every time a cylinder or motor starts up, until the steady-state velocity of the piston matches the flow rate from the pump.

In the time interval $dt < t < \Delta t$, the external portions of the system start to move. Two changes in loading take place:

1. An acceleration force $F = ma$ is introduced in accordance with Newton's second law of motion.
2. The friction force drops from static friction conditions to dynamic friction conditions. Of course, this occurs because the coefficient of static friction is greater than that for kinetic friction.

At the end of the time interval Δt, we note that the piston has reached steady-state velocity $v_{ss} = Q/A_p$. When this occurs, the acceleration force disappears and the steady-state load reduces to components of dynamic friction and external load.

Does this mean that the steady-state load is constant? Certainly not! It is important that the circuit designer recognize this fact, particularly when she or he is dealing with multibranched circuits operating with one pump. In such cases, auxiliary controls, or flow dividers, may be necessary. The designer will not know this unless a complete picture of the load cycle is produced.

A typical load reaction plot for the hoist cylinder on our excavator is shown in Fig. 42.7. This plot must be determined from a layout of the arm and bucket mechanism at different angles during the complete range of motion.

A similar plot must be made for each actuator on the machine. Where does the circuit designer get this information? From the machine designer, who had to go through the analysis in order to engineer the machine in the first place.

When the designer has made individual load-cycle plots for each actuator, then he or she must consider them against the sequence plot to determine simultaneous operation. When the comparison indicates that two critical operations occur at the same time, the designer should consider separating the actuators rather than installing them as branches of the same circuit. (By definition, a circuit, whether single or multibranched, is fed by a single energy source, or pump.) The reason for separating critical functions is that in a multiple-actuator circuit, the actuator requiring the lowest pressure will take *all* the fluid. Besides the inconvenience of not having one of the critical operations occur, there is the danger of dropping load as a result of a change in pressure relationships owing to motion of the system.

The complete load plot for a single actuator might look like Fig. 42.8.

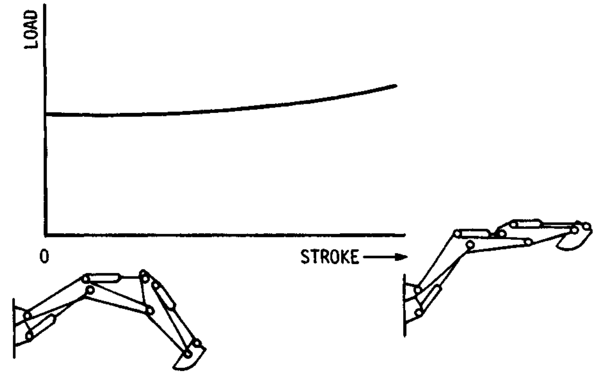

FIGURE 42.7 A load reaction plot for the hoist cylinder. *(From Ref. [42.1].)*

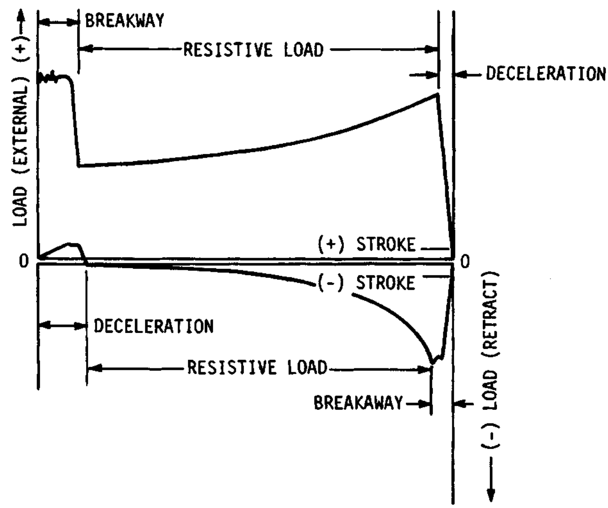

FIGURE 42.8 Load plot for a single actuator. *(From Ref. [42.1].)*

REFERENCES

42.1 Russell W. Henke, P. E., *Fluid Power Systems and Circuits,* Penton/IPC, Cleveland, 1983.

42.2 ANSI standard Y32, 10-1967 (R1979), "Graphic Symbols for Fluid Power Diagrams."

42.3 Russell W. Henke, *Introduction to Fluid Mechanics,* Addison-Wesley, Reading, Mass., 1966.

42.4 William Wolansky, John Negoshian, and Russ Henke, *Fundamentals of Fluid Power,* Houghton Mifflin, Boston, 1977.