WHAT'S WRONG WITH ENERGY UTILIZATION IN HYDRAULIC CRANES

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ABSTRACT

In this paper a short review on control strategy development of hydraulic crane systems is given. Energy utilization for different alternative driving concepts in an example hydraulic crane is evaluated and compared for a typical duty cycle. The possible factors that result in poor energy utilization and low efficiencies are analyzed and discussed. The answers to the question *what is wrong with energy utilization in hydraulic cranes* are tried to look for. On the other hand the suggestions that might improve energy utilization in hydraulic crane systems are presented.

KEYWORDS: hydraulic crane, energy utilization, efficiency

INTRODUCTION

Hydraulic cranes are multi-link hydraulic booms. They are widely used in mining and rock excavation and drilling, forest harvesting, construction material handling and harbor terminal activities. In recent years hydraulic crane design has been influenced more and more by call for increased performance and enhanced cost-efficiency for users faced with price and cost pressure, environmental requirement, etc. Therefore how to improve energy efficiency and minimize energy loss in crane systems is an important scheme for industries and designers.

Great research works have been done concerning the theoretical and practical benefits from the application of energy efficient strategies in hydraulic systems. Liang, Virvalo and Linjama [1] compared the influence of control valves on energy efficiencies in a Loglift loader. Andersson [2] analyzed the performances different mobile valve applications including their controllabilities and power losses and also he discussed current technology and future development of LS directional valves. Backé [3] gave general description about the energy efficiencies of different pump and valve control strategies. Weber [4] discussed Controlling pumps for performance and efficiency.

This paper consists of a short review on control strategy development of hydraulic crane systems. Energy utilization of different alternative driving concepts in an example hydraulic crane is analyzed and evaluated. The answers to the poor utilization of energy are tried to look for. On the other hand the methods that might improve energy utilization in hydraulic crane systems are suggested.

TYPICAL DRIVE CONCEPTS

With the development of hydraulic technology, different drive concepts and control strategies of hydraulic valves and pumps have been used in industrial cranes. Table 1 describes the brief principles of the representative drive concepts, *p-Q* diagrams and simplified models and efficiencies of hydraulic systems. Normally each of crane links is driven by one function of valve-controlled cylinder and all of them are powered by one common hydraulic pump except for Table 1-e.

Their energy losses are reduced and their efficiencies are improved in proper order from (a) to (e) in Table 1, where their efficiency calculation are obtained based on some given conditions.

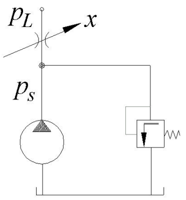
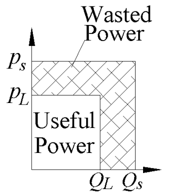
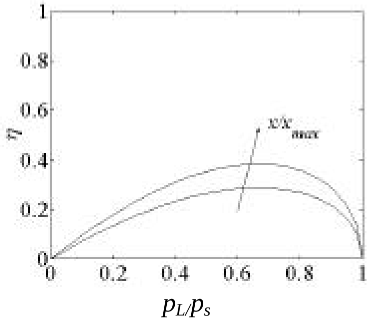
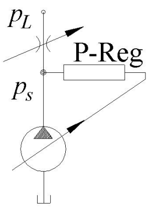
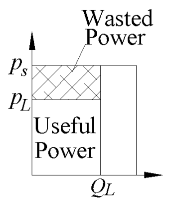
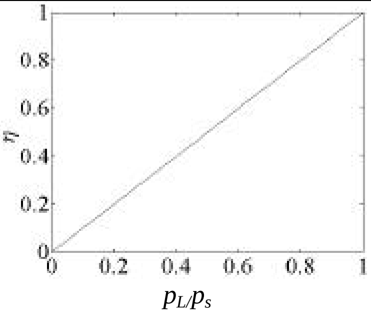
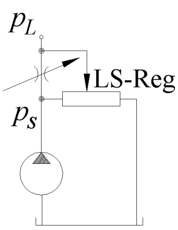
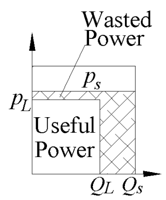
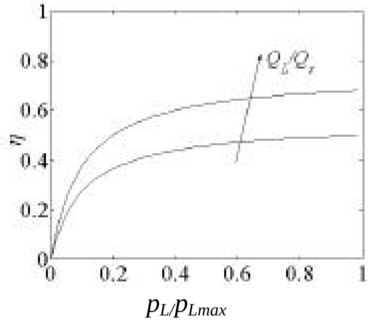
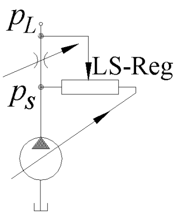
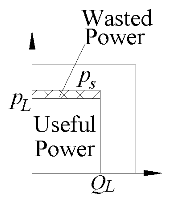
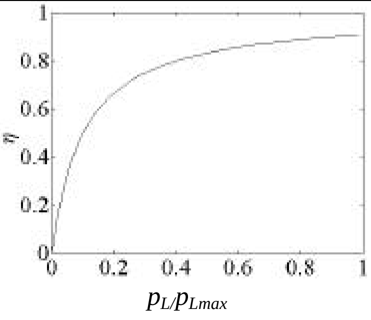
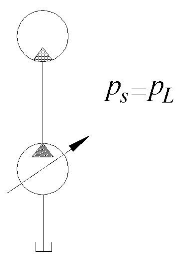
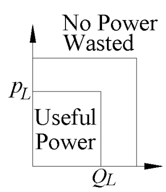
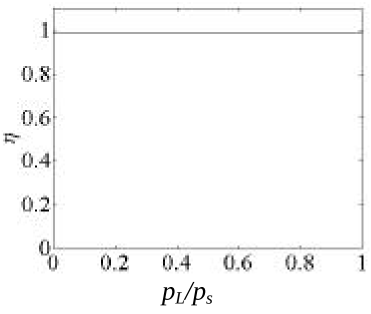
(1) Conventional Control

Table 1-a describes a conventional system where a fixed displacement pump is controlled by a relief valve. Its outputs of flow and pressure are in excess of the load requirements. Therefore surplus flow and pressure from hydraulic pump produce large losses. However the whole system is simple, reliable and inexpensive, especially it has good controllability.

(2) Variable Flow Control

This concept in Table 1-b is defined as that it can adapt the pump supply flow to the load motion requirements precisely or rather it has no surplus flow into the system. It can save energy and improve the system efficiency for it can minimize the losses dependent on flow. There are different methods to realize this strategy. Anyway it is necessary to utilize a variable pump.

Table 1 Typical driving concepts in hydraulic cranes

No	Systems	*p*-*Q*	Models	Efficiency *ç**
a			p_s=constant Q_s=constant $h =$ $\frac{p_L}{p_s}\sqrt{1-\frac{p_L}{p_s}}\times\frac{x}{x_{max}}$	
b			p_s=constant Q_s=variable(=Q_L) $h = \frac{p_L}{p_s}$	
c			p_s=p_L+ p_s Q_s=constant p_s=constant $h =$ $\frac{1}{1+\Delta p_s/p_L}\times\frac{Q_L}{Q_S}$	
d			p_s=p_L+ p_s Q_s=variable(=Q_L) p_s=constant $h = \frac{1}{1+\Delta p_s/p_L}$	
e			Q_s=variable(=Q_L) p_s=p_L $h = 1$	

**Some assumptions are made*

(3) Variable Pressure Control

Variable pressure control can minimize the surplus pressure. Very often this drive is characterized by the fact that the load pressure is fed to pump regulator and the pump pressure is controlled by the pump regulator to always be a certain value Δp_s higher than that the actual load needs. So a fixed pump may be used for this drive without the consideration of variable flow requirement. Table 1-c describes a typical pressure load-sensing system with a fixed pump.

(4) Variable Flow and Pressure Control

Variable flow system cannot resolve the problem of pressure surplus, and variable pressure system cannot resolve the problem of flow surplus. The LS system with variable flow control may be the best choice to improve the system efficiency. Table 1-d shows its simple theory.

(5) Pure Pump Control

Pure pump control, shown in Table 1-e, is not a new idea. The similar application is pump-motor integrated unit in some special heavy vehicle. There are a lot of research works to do when this concept is used for a hydraulic crane or robot wherein normally it is called as integrated hydraulic servo joint actuators. Grabbel and Ivantysynova [5] discussed its advantages and possibilities applied in a hydraulic manipulator. However they did not show its verified experiment. Perhaps in the not too long future it would be possible applied in an industrial crane. Theoretically it is very energy efficient due to separate joint drive.

ENERGY EFFICIENCY EVALUATION

Different drive concepts in Table 1 (a~d) have ever been applied in hydraulic cranes. Naturally their influences on energy efficiencies are different. The following analysis is hoped to reveal their energy utilization in an example hydraulic crane.

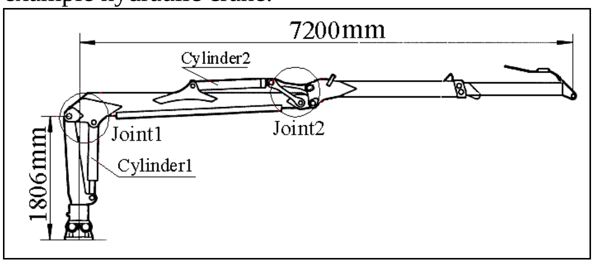


Fig. 1 An example hydraulic crane

(1) An Example Crane

The crane, shown in Fig.1, is a Loglift loader. It has four main DOFs: rotating, lifting, transferring, and telescope. **Fig**.2 illustrates its workspace and an assumed duty cycle ABC where the work paths of the boom endpoint start from point C and then to point B and to point A without load. At point A the crane catches a 500kg load. After that the boom continues back along the inverse direction from A to B to C with the 500 kg load, and unload it at point C. The whole period *T* is about 11 seconds. During the total period only Joint 1 and Joint 2 work simultaneously and share a common pump. Other joints have no movement.

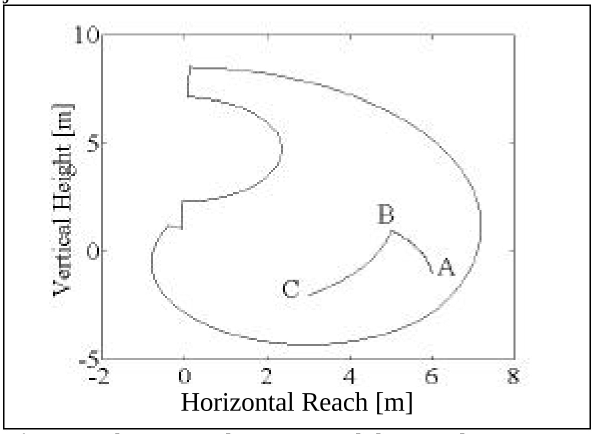


Fig.2 Workspace and an assumed duty cycle ABC

(2) Energy Equations

Power and energy transfer in the crane system can be evaluated according to the following models:

The power loss P_{loss} and energy loss E_{loss} are calculated by equation (1) and (2), respectively:

$$P_{loss} = \sum_{i=1}^{k} (P_{in} - P_{mech}) \qquad (1)$$

$$E_{loss} = \int_0^t P_{loss} dt \qquad (2)$$

The pump supply energy E_{pump} is given by

$$E_{pump} = \int_0^t p_s Q_s dt \qquad (3)$$

The overall efficiency of the crane system for a duty cycle t=T is as follows:

$$\eta_{oa} = \frac{\int_0^T \sum_{i=1}^{n} P_{mech} dt \Big|_{P_{mech} \geq 0}}{E_{pump}} 100\% \qquad (4)$$

where,

P_{in} — power from pump into valve
P_{mech} — mechanical power
P_{loss} — power loss
E_{loss} — energy loss
E_{pump} — pump supply energy
p_s — pump pressure output
Q_s — pump flow output
η_{oa} — overall average efficiency
k — number of operating joint

(3) Energy Evaluation and Efficiency Calculation

All the functions of each crane system are parallel connection to each other and also they are powered by one pump. Every joint is driven by the mode of valve controlled cylinder.

Fig 3 depicts the overall hydraulic energy consumption of four typical drive concepts (a~d) in Table 1 for the same work cycle.

Their overall average efficiencies are given in Table 2. By the way it needs be pointed out that efficiency calculations in Table 1 are comparative results at some power points and they are not useful to evaluate the practical energy utilization for some duty cycles in a hydraulic crane.

Of all the discussed four drive concepts, the system with variable flow and pressure has the least hydraulic energy consumption and the highest efficiency for the same assumed cycle.

The above calculations are obtained without any consideration of other factors that influence system efficiency, such as leakage and mechanical loss, pipe/hose loss, friction, etc.

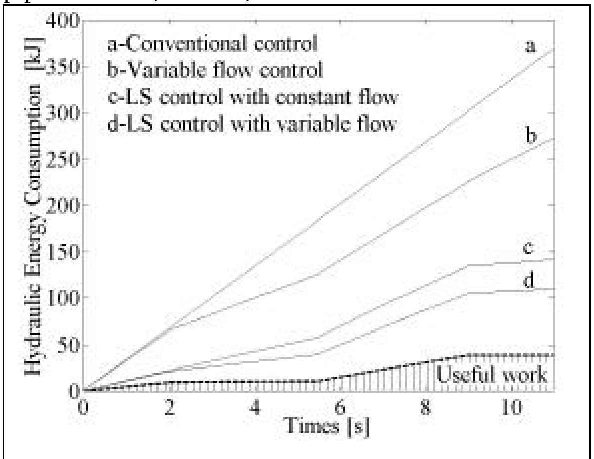


Fig.3 Hydraulic energy consumption of various crane systems for the duty cycle

RESULTS

The energy transmission and overall average efficiencies of four alternative hydraulic systems have been analyzed and evaluated for the given cycle. The result shows that the three drives (c~e) in Table 1 have better energy utilization and greater efficiency improvement than the conventional system (a). Especially the variable flow and pressure system has the highest efficiency. From the viewpoints of saving energy, the variable flow and pressure system is the best choice for a hydraulic crane. In theory pump-motor integrated servo joint would have very ideal energy utilization in hydraulic cranes. However no public description of its real experiment and successful application in some hydraulic cranes can be found. So here it is not discussed in detail.

Of course when the control strategies of a hydraulic system is selected, it is necessary to consider the system cost, dynamic performances, controllability, etc.

Anyway it is obvious that energy utilization in the crane system is not so good as expected, such as the overall efficiency of the variable flow and pressure system is about 35.55% for the specified cycle. Therefore it should be accepted that energy utilization in the hydraulic system is poor.

For many years researchers have been trying to find the answers to the question what's wrong with energy utilization in hydraulic cranes.

DISCUSSIONS

It is evident that energy efficiencies of four typical drive concepts are very low. Thus hydraulic power is wasted seriously. Energy efficiencies in a hydraulic crane cannot be improved as greatly as expected even if flow and pressure variable system is used. The values of efficiencies are a little lower than those in Table 2 when the practical factors are considered that cause flow and pressure losses, such as leakage, pipe/hose loss, friction, etc. Energy losses from surplus flow supply can be minimized through a variable pump and surplus pressure supply in an LS system can be reduced as much as possible. Very often we have to face the problems: What's wrong with energy utilization in a hydraulic crane? In fact it is not very difficult to analyze the basic causes:

A. Surplus supply of hydraulic power from pump does exist in the above four systems. Although it has no flow loss, the system with variable flow and pressure control still has pressure loss $Äp_s$ (please see its *p*-*Q* diagram in Table 1).

B. No matter whether resistive or overrunning the load force on a cylinder is, one-joint operation and control is very favorable to save pump power output in an LS system. However energy losses in the system are still large for an overrunning load. Moreover the majority of them could be transferred into heat. Fig.4 describes the practical measurement of cylinder 1 for a 500kg load at the crane endpoint, where u_1 is control signal of LS valve. For the upward movement in Fig.4(a), the load force is resistive thus pump pressure p_s has a certain value higher than load pressure p_A. However for the downward movement the load force is overrunning, so p_s remains the lowest constant pressure output regardless of load force change. Meanwhile p_A is much higher than p_s in order to control load motion by throttling. In this case the throttling loss is mainly from the potential energy of lifted load and link weight according to the theory of energy conservation.

C. For multi-joint operation and control, LS systems don't improve energy utilization as ideal as expected. Very typically several actuators in a hydraulic crane are powered by one common pump. In an LS system, its pump pressure is dependent on the maximum load pressure of actuators, but it cannot make its pressure adapt several actuators as precisely as possible, respectively. Therefore there are surplus pressure supply and large power losses in the other functions of lower load pressures.

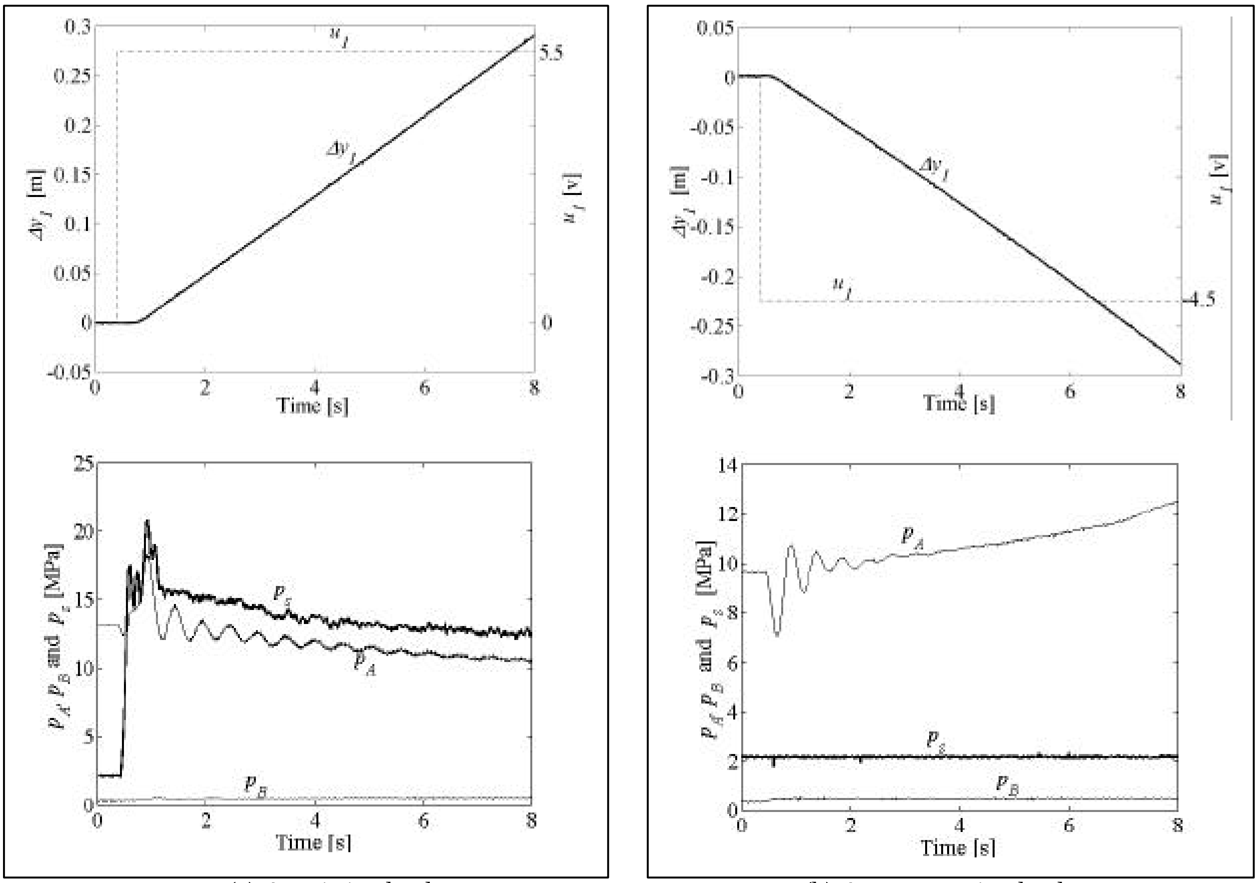
D. The characteristic of load forces on joints and cylinders in a hydraulic crane is an important factor. Load forces on different cylinders have large differences. Resistive and overrunning load forces alternatively actuate on the cylinders because the cylinders are required for instroke or outstroke motions. Sometimes the direction of some load forces is variable along some work paths. All these could result in large pressure losses.

E. A hydraulic crane is one of typical lifting machinery. It is easy to be accepted that lifted load and link weight do work due to its potential position change. When it is operated for a downward movement, the work would result in large throttling losses. Therefore it is not the sole way to reduce energy losses by minimizing hydraulic energy.

F. Energy efficient path selection is worth of careful consideration. It is very possible to find more energy saving paths for the customer's purpose than the assumed cycle ABC.

Table 2. Overall average efficiency

driving strategies	conventional system	variable flow system	variable pressure system	variable flow and pressure system
h_{oa}	10.62%	14.36%	27.40%	35.55%



(a) A resistive load
(b) An overrunning load

Fig.4 Measured for one-joint control in an ELS system*

*u_1—control signal of LS valve; Äy_1—relative position change of cylinder 1; p_A—pressure in the chamber without piston rod; p_B—pressure in the chamber with piston rod

SUGGESTIONS

Here we want to take risk to give some possible suggestions that might improve energy utilization in hydraulic cranes. Some of them are the topics that our co-workers and we have been working at. What we advise is not to imagine creative work in the future but based on our possible technologies at present.

a. **Further enhanced application of energy efficient controls** of flow and pressure or other relevant parameters for hydraulic components and systems. All the ways would be able to minimize hydraulic pump power and energy losses in their systems.

b. **Multi-pump system application**. Normally hydraulic crane application need be combined with other endpoint lifting devices. Thus it is beneficial to use two or three pumps to supply energy to different hydraulic actuators according to different force demands. Pump-motor integrated joint for hydraulic cranes would be interesting after its further development.

c. **Energy storage and reutilization**. The practical experiments have shown that it can save pump power, reduce the throttling losses in the system and improve energy utilization [6].

d. **Optimization application**
Optimization of system parameters.
Optimal cylinder positions for some defined paths in the workspace.
Energy efficient path and motion controls based on some optimal objective functions. Today's crane technology is not confined to manual operation. Some of them have been able to realize refeed control or more complicated control for some special purposes.

Naturally the sealing, leakage, friction of components and systems is still worth considering and caring.

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