Comparison of power density of transmission elements in hydraulic, pneumatic, and electric drive systems

Toshiharu KAZAMA*
*College of Design and Manufacturing Technology, Muroran Institute of Technology
27-1 Mizumoto-cho, Muroran, Hokkaido 050-8585, Japan
E-mail: kazama@mmm.muroran-it.ac.jp

Received: 12 March 2019; Revised: 27 August 2019; Accepted: 24 September 2019

Abstract
This paper explores the transmittable power of power transmission elements in fluid power and electric drive systems. We consider a simple model for the piping in hydraulic and pneumatic systems that ignores the fittings and auxiliary equipment and the wiring in electric drive systems that ignores the terminals and auxiliary equipment. We analyze the data based on specifications of hoses for hydraulic systems, tubes for pneumatic systems, and cables for electric drive systems from the manufacturers’ catalogs. We survey the outer and inner diameters, mass per unit length, maximum working pressure, mean flow velocity, rated voltage, and rated current to estimate the maximum transmitted power and examine the relationship between the power and the size and weight and calculate the power density. The influences of mass of oil, return lines of hydraulic circuit, materials of pneumatic tubes, and number of cable cores are also discussed. In conclusion, the transmittable power of the elements of all systems can be approximated by a power function for the mass per unit length. The relation between the transmittable power and the mass for hoses, tubes, and wires is similar. The power density of hydraulic hoses and electrical cables is high; the power density of pneumatic tubes is low. Oil in the pipes and return lines of hydraulic systems is not negligible.

Keywords: Fluid power, Hydraulics, Pneumatics, Electricity, Power density, Piping, Wiring, Characteristics comparison

1. Introduction

Fluid power (hydraulic and pneumatic) systems and electric drive systems are used commonly and extensively across industries and society (JHPS, 1989). Although each of these systems has its own unique characteristics, the relative merits and demerits have been discussed. Comparisons of the power density and acceleration performance (JFPS, 2003) by a few researchers (Urata, 1985; Foster & Fenney, 1989; Nakano & Konno, 1997) concluded that hydraulics show the highest power density, that each system has its own appropriate areas of application, and that selection should not be limited to one system type. The evaluation targets were actuators, motors, and pumps and the evaluated parameters were rated torque, torque-inertia ratio, power-to-weight ratio, and weight of the components (Tanaka et al., 2013). This approach is logical because these form the primary components of such systems and have significant weight.

The connecting elements in the system, namely, pipes or wires, should also be investigated because the weight ratio of piping in construction machinery reaches about 0.5–1 percent (Hanada et al., 2012) and many wire harnesses are used in electric cars and vehicles. In this study, we focus on hoses in hydraulic systems, tubes in pneumatic systems, and wires in electric drive systems, compare the individual characteristics and transmittable power, and discuss the differences and merits.

2. Nomenclature

\[ D_i \quad \text{inner diameter} \]
\[ D_o \quad \text{outer diameter} \]
3. Power transmission elements

Hydraulic, pneumatic, and electric systems are used in many applications over a wide range in terms of scale and configuration. This study models hoses, tubes, and wires from the power source to the actuator for the simple circuits shown in Fig. 1.

\[
P = pQ = \frac{\pi D_i^2 pU}{4}
\]

where \( D_i \) is the inner diameter, \( p \) is the pressure, \( Q \) is the volumetric flow rate, and \( U \) is the mean velocity. In an electric drive system, when the power factor is assumed to be 100% and the electrical resistance and voltage drop are zero, the effective power is equivalent to the apparent power \( P \):

\[
P = EI
\]

where \( E \) is the voltage and \( I \) is the current.

Data on the inner and outer radii and mass per unit length of hoses, tubes, and cables, the maximum working pressure of hoses and tubes, and the rated voltage and rated current of cables were obtained from the representative manufacturers’ catalogs available on the Internet.

3.1 Hydraulic hoses

The energy transfer medium is hydraulic oil and the transmission element is piping. Piping elements have a variety of uses, but can be categorized into steel pipes and rubber hoses. Hoses are selected here because of their flexibility, while steel pipes are rigid. These are standardized and produced with different inner diameters and thicknesses based on the required flow rates and pressures. In this study, we selected general-purpose hydraulic hoses for mineral oil produced...
by three manufacturers with maximum operating pressures of 3.5, 7, 10.5, 14, 17, 20.5, 27.5, and 34.5 MPa.

Figure 2 shows a graph of the transmitted power $P$ [kW] versus the mass per unit length $m'$ [kg/m] and Fig. 3 shows the transmitted power versus the outer diameter $D_o$ [mm]. In calculating the power $P$, we assume that the mean velocity $U = 5$ m/s which is based on the recommendation maximum velocity in a high pressure line (JIS B8361, 2013) and the pressure $p$ is the maximum working pressure. The relationship between the power and the mass per unit length and diameter is approximately as a power law, given by:

$$
\begin{align*}
P[kW] &= A(m'[kg/m])^a \\
P[kW] &= B(D_o[mm])^b 
\end{align*}
$$

(3)

![Fig. 2 Mass per unit length $m'$ vs. transmitted power $P$ for hydraulic hoses](image1)

![Fig. 3 Outer diameter $D_o$ vs. transmitted power $P$ for hydraulic hoses](image2)

The least-squares method gave exponent $a$ as $m'$ as 1.4 and exponent $b$ as $D_o$ as 2.7 (coefficient $A$ as $m'$ as 20.7 and exponent $B$ as $D_o$ as 0.002) in Eq.(3). The coefficient of determination $R^2$ for $m'$ ($R^2 = 0.92$) was closer to unity than it was for $D_o$ ($R^2 = 0.82$), while the range of $m'$ was approximately 1–2 order larger than the range of $D_o$. It is mentioned that $a$ and $b$ are independent of $U$, while $A$ and $B$ are proportional to $U$. That is, for example, $P$ becomes half if $U$ is halved.
In actual situation hydraulic hoses are filled with oil during operation and hydraulic systems need return lines. Figure 4 illustrates the transmitted power $P$ when the hoses in the pressure line (one-way) $[m' + M']$ and in the pressure and return lines (two-way) $[2(m' + M')]$ are filled with hydraulic oil, where the density of oil $\rho = 900 \, \text{kg/m}^3$, the mass of oil in a hose per unit length $M' = \pi \rho D_i^2/4$, and $U = 5 \, \text{m/s}$. Assuming that the actuator is a double-acting cylinder, the hoses for the majority of the return lines can be the same as the supply line hoses. Although low-pressure hoses with a large cross section are often selected for return lines because the oil pressure is generally low or almost equal to atmospheric pressure. As the graph in Fig. 4 shows, the transmittable power decreases when the hoses are filled with oil and there are return lines.

![Graph showing hydraulic transmission power $P$ vs. mass ($m'$ and $M'$) per unit length for supply and return lines filled with oil.]

**3.2 Pneumatic tubes**

When the energy transfer medium is compressed air, the transmission element is piping. Piping elements can be categorized into metal pipes and resin tubes. We selected general-purpose pneumatic tubes produced by three manufacturers.

Although air is compressible and compressed air has expansive energy, the pneumatic transmission power can also be represented by Eq. (1) (Cai et al., 2005). The relationship between the mass per unit length $m'$ and the transmitted power $P$ is shown in Fig. 5. Flexible tubes are primarily made of nylon or urethane, so we examined these two types. In this report a mean velocity is set at $U = 15 \, \text{m/s}$ for reference (JMF and JFPA, 2008), even though $U$ can take under 10 m/s (or 5 m/s) and over 30 m/s (or 100 m/s) (JIS B8370, 2013; Takahashi, 1995). The maximum working pressure of each tube was assumed in calculating the power $P$. While there are smaller variations for urethane than for nylon, for urethane is 2–4 times smaller than for nylon. The exponent $a$ of 1.3 (nylon) and of 1.2 (urethane) were almost equivalent. The relationship between $P$ and $m'$ for tubes is similar to that for hoses. However, the transmitted power for tubes is notably smaller than that for hoses by about two powers under these conditions.
3.3 Electrical wiring

The energy transfer medium is electricity (electric charges) and the transmission element is wiring. Wiring elements can be categorized into cables and wires. As there are many varieties, we targeted 2-, 3-, and 4-core 600-V general-purpose cable wire cables produced by three manufacturers. The transmittable power $P$ was calculated at the rated voltage ($E = 600 \text{ V}$) and the maximum rated current of each cable. Figure 6 is a graph of $P$ against $m'$ showing the data points and the lines of best fit. The exponent $a$ in Eq. (3) was taken as $0.79 - 0.82$, reflecting the difference in the number of cores. In addition, the dispersion of the power in electric drive systems in terms of mass per unit length (and the outer diameter of the cable) is smaller than for hoses and tubes.

3.4 Comparison of transmittable power

Figure 7 shows a comparison of the transmittable power of hydraulic, pneumatic, and electric drive systems with the assumptions of the model used in this study, and assuming that the rubber hoses, urethane tubes, and three-core cables form a single supply line. The values are calculated at a working pressure and $U = 5 \text{ m/s}$ for the hoses and $U = 15 \text{ m/s}$ for the tubes and at a rated current and $E = 600 \text{ V}$ for the cables. It is to be noted that, in a sense, this value of $E$ is an upper limit based on product specification. The graph shows a clear division in the range of the hydraulic and pneumatic systems, the former covering the higher power region and the latter covering the lower power region. The value of the transmittable power in a hydraulic and electric drive system is almost the same, namely, these characteristics are
Comparing both systems, under high power conditions, hydraulic systems show an advantage over electric drive systems; however, electric power exceeds hydraulic power close to the middle range. In this study, the following relationship was obtained between \( m' \) and \( P \) in the ranges \( 10^{-3} < m' [\text{kg/m}] < 10^{2} \) and \( 10^{-3} < P [\text{kW}] < 10^{3} \).

\[
P \propto m'^n
\]  

(4)

wherein, \( n = 1.3 \) in Fig. 7. Each exponent for hoses, tubes, and cables was 1.4, 1.2, and 0.8, respectively. These exponents, with the possibility of changing, are not influenced by \( U \) and \( E \), but \( n \) depends on these parameters.

In addition, we calculated the ratio of the power to the mass per unit length, namely the power density \( P/m' \). We obtained values of \( P/m' = 54–1.6 \text{ kW/(kg/m)} \) for hydraulic hoses with \( U = 5 \text{ m/s} \), 13.2–4.7 \text{ kW/(kg/m)} \) for pneumatic tubes with \( U = 15 \text{ m/s} \), and 51–25 \text{ kW/(kg/m)} \) for electrical cables with \( E = 600 \text{ V} \). These solutions depend on not only product data, but also the numerical values, e.g., \( P/m' = 65–1.0 \text{ kW/(kg/m)} \) if \( U \) is 6–3 \text{ m/s} \) for hoses (JFPS, 1989); \( P/m' = 26–1.6 \text{ kW/(kg/m)} \) if \( U \) is 30–5 \text{ m/s} \) for tubes; \( P/m' = 51–4.2 \text{ kW/(kg/m)} \) if \( E \) is 600–100 \text{ V} \) for cables. The overlapping regions increase but the order of the power density is not essentially changed.

Although the data and conditions are limited, an overview in terms of transmittable power of the transmission elements may be drawn: Hydraulic hoses showed the highest power density across the largest region and pneumatic tubes showed the lowest. Hoses can transmit power across a large region and cables across a middle region. Moreover, hydraulic hoses are for heavy applications and in contrast, pneumatic tubes are for light applications; the former is applicable to the power transmission systems roughly from kilo-watts to mega-watts and the latter is suitable from kilo-watts to watts, in which the power is covered across a wide range on the order of \( 10^6 \). Interestingly, the exponents of the power law between the transmittable power and the mass per unit length for hoses, tubes, and cables are close to unity, whereas the exponents for pipes (hoses and tubes) are above unity and that for wires (cables) is below unity. Regarding the pipes, the exponents are almost the similar, though the working fluids and operating conditions are different and thus materials and structures are also different. Further, the exponent for wires is not far from that for pipes, though there is a significant difference in functions and usage. One can see that the transmission elements would be partially related to specific strength (Ashby, 1992).

Fig. 7 Comparison of the relationship between transmittable power \( P \) and mass per unit length \( m' \) for the power transmission elements of hydraulic hoses (\( U = 5 \text{ m/s} \)), pneumatic tubes (\( U = 15 \text{ m/s} \)), and electrical cables (\( E = 600 \text{ V} \))

4. Conclusion

The transmittable power of hydraulic, pneumatic, and electric drive systems are examined using a basic model consisting simply of universal rubber hoses for hydraulic systems, thermoplastic tubes for pneumatic systems, and cabtyre cables for electric drive systems. Only these transmitting elements are considered and no drop in pressure or voltage is
assumed. The data were collected from manufacturers’ catalogs available on the Internet and the power at which maximum transmission was possible was estimated under a limited condition. The relationships between transmittable power, mass per unit length and outer diameter were explored.

In conclusion, the transmittable power of hydraulic, pneumatic, and electric drive systems can be expressed approximately as a power function across a wide range of weight and size. The exponents for hoses and tubes are almost the same and the exponents between pipes and wires are close to each other despite the difference in function and materials. Hydraulic hoses demonstrated the largest transmittable power in a wide range, especially under high power conditions, and pneumatic tubes demonstrated the lowest transmittable power, although the transmittable power of hoses and electrical wires was comparable. Oil in the hoses and return circuits of hydraulic systems decreases the transmittable power. The features of these transmission elements are almost similar to the features of actuators; that is, those resulting from the comparison between hydraulic and electric motors.

References

Ashby, M. F., Materials Selection in Mechanical Design, Pergamon Press, (1992).
Cai, C., Kawashima, K., and Kagawa, T., Power assessment of flowing compressed air, Transactions of the ASME, Journal of Fluids Engineering, Vol. 128, No. 2, (2005), pp. 402–405.
Foster, K. and Fenney, L., Characteristics and dynamic performance of electrical and hydraulic servo-drives, Proceedings of the JFPS International Symposium on Fluid Power, Issue 1, (1989), pp. 15–22.
Hanada, Y., Hamade, K., Hirosawa, A., Abe, K., and Nabeoka, K., Development of chlorine free hose for construction machinery to raise recyclability rate, Komatsu Technical Report, Vol. 58, No. 165, (2012), pp. 16–22 (in Japanese).
JEAC, Interior Wiring Code, The Japan Electric Association, (1990) (in Japanese).
JFPS, Special issue “Electric actuator? or fluidic actuator”, Journal of the Japan Fluid Power System, Vol. 34, No. 2, (2003) (in Japanese).
JHPS, Handbook of Hydraulics and Pneumatics, The Japan Hydraulics and Pneumatic Society, (1989) (in Japanese).
JIS, B8361, Hydraulic fluid power-General rules and safety requirements for systems and their components, Japanese Standards Association, (2013) (in Japanese).
JIS, B8370, Pneumatic fluid power-General rules and safety requirements for systems and their components, Japanese Standards Association, (2013) (in Japanese).
JMF and JFPA, Research report (http://www.jmf.or.jp/houkokusho/7/436.html), Japan Machinery Federation, (2008) (in Japanese).
Nakano, K. and Konno, Y., The comparative study on the characteristics of ac, dc servomotors and hydraulic motors, Journal of the Japan Hydraulics & Pneumatics Society, Vol. 28, No. 4, (1997), pp. 466–472 (in Japanese).
Takahashi, T., Basics and Applications to Pneumatics, Tokyo Denki University Press, (1995) (in Japanese).
Tanaka, Y., Sakama, S., Nakano, K., and Kosodo, H., Comparative study on dynamic characteristics of hydraulic, pneumatic, and electric motors, Proceedings of the ASME/BATH 2013 Symposium on Fluid Power & Motion Control, FPMC2013-4459, (2013), V001T01A037.
Urata, E., Power density and force density, Power Design, Vol. 22, No. 10, (1985), pp. 46–57 (in Japanese).