Development of a novel compact hydraulic power unit for the exoskeleton robot

Xiaoping Ouyang\textsuperscript{a,*}, Shuo Ding\textsuperscript{a}, Boqian Fan\textsuperscript{a}, Perry Y. Li\textsuperscript{b}, Huaying Yang\textsuperscript{a}

\textsuperscript{a} State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, PR China
\textsuperscript{b} Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, USA

\section*{A R T I C L E   I N F O}

Article history:
Received 25 January 2016
Revised 9 June 2016
Accepted 15 June 2016
Available online 13 July 2016

Keywords:
Exoskeleton robot
Hydraulic power unit
High specific power
Model
Parameters identification

\section*{A B S T R A C T}

Exoskeleton robots require powerful and lightweight power supplies. Because of its high power-to-mass ratio and fast response, hydraulic systems can meet the requirement for locomotion robots. In this paper, a novel compact hydraulic power unit (CHPU) is proposed. A two-stroke IC engine, with a rated power of 2.4 kW at 13,000 rpm, is used as the prime mover. The engine drives a high speed (10,000 rpm) piston pump to allow the engine to operate at high power. A spring loaded reservoir has been developed to prevent the pump intake from cavitation and contamination. The payload flow rate is indirectly estimated using the displacements of the actuator. A Ragone plot analysis shows that the CHPU can maintain a high specific power over a long duration. A dynamic model for the CHPU has been developed based upon simplified engine operating characteristics and a set of experimentally identified parameters. A prototype of the CHPU has been constructed with a rated power of 1.45 kW and a weight of 16.6 kg. Experimental testing of the prototype confirms the dynamic model and the output capacity of the CHPU.

\section*{1. Introduction}

Exoskeleton robots can play an important role in many occasions by enhancing the wearer's strength and endurance. Many exoskeleton robot prototypes have been successfully developed such as BLEEX [12], HULC and XOS [3,4] for field use as well HAL [5], LOPES [6], NeXOS [7], energy harvesting exoskeleton [8] and Octopus inspired Robot [9,10] for normal life use and rehabilitation.

In many applications, high load carrying capacity, long working hour, as well as fast energy supply are necessary. Therefore exoskeleton robot requires a powerful, lightweight and easily supplied power unit. Several kinds of actuation have been used in the exoskeleton robot. Using the electromotor is a convenient way to drive the joints, but the output driving torque won't be very large for the limitation of the size of the motor. Besides, the joint structure will be swollen with the motor and the speed reducer. Pneumatic is another way to drive the robot joint, however, the accurate position control of the pneumatic muscle is difficult and the big air source is hard to integrate into the robot either. Hydraulic system has high power-to-mass ratio, fast dynamic response and large force output. These advantages make it provide the high load carrying capacity and many locomotion robotics such as Bigdog [11] and HyQ [12,13] use hydraulic systems as their drive system.

The XOS exoskeleton robot uses an external hydraulic power unit located on the ground, so that the total mass of the robot is decreased and the energy can be quite enough for a long working time, however the XOS cannot work far from the power unit as the result of the limitation of the length of the hoses. A hydraulic-electric power unit (HEPU) based on an engine was built and demonstrated on the BLEEX. The HEPU prototype weighs 27 kg and produces 2.52 kW total power. HEPU uses a solenoid valve to regulate the hydraulic system. However, due to rapid transient of the hydraulic power demand, sudden increase of the engine load torque often happens causing the engine stall. In addition, a part of high-pressure hydraulic flow goes directly to the reservoir, producing energy waste and excessive heat. The HULC exoskeleton robot uses a battery as the prime mover of the hydraulic power unit. However, due to the low specific energy of the battery, it is hard to achieve long working time. Furthermore, as a robot applied in battlefield, battery charging may be a tough problem for HULC.

\textbf{Table 1} shows several power sources possible used in the robotic field. The gasoline engine has very high actual energy density even though its efficiency is low (15.8\% in this paper). The actual energy density of Li-ion battery is much lower than the engine [14], and so as to the free piston hydraulic pump (FPHP) based on monopropellants developed at UC Berkeley [15]. Fuel cells can provide very high energy density and efficiency [16], but
only electric energy. The transmission to hydraulic power will be heavy and decrease the overall efficiency. Besides, this technology is still not matured enough to be integrated in a wearable robot. From the above, the internal combustion engine is employed in the CHPU for its high specific energy and the fast refueling.

This paper presents a novel compact hydraulic power unit (named CHPU) powered by an internal combustion engine. The CHPU has a high specific power and can be easily integrated. In the transmission chain, a high speed pressure-compensated piston pump with 10,000 rpm is used for improving the power density highly. Meanwhile, the engine stall and the power waste caused by the switching valve regulation in [1] are also avoided by the pump. The spring loaded reservoir employed in the CHPU assists the high speed pump working well and reducing the reservoir dimensions. Finally, the dynamic model of the CHPU is built and the performance of the CHPU is validated by the prototype test.

The remainder of this paper offers the following:

Section 2 presented the analysis of pressure and flow rate requirement based on a lower extremity exoskeleton.

Section 3 presented the overview and main characteristics of the CHPU.

In section 4, model of the CHPU was built and the physical parameters were identified by using least square method.

Section 5 showed the tests result carried out on the CHPU prototype. Section 6 concludes.

2. Load requirements

2.1. Lower extremity exoskeleton structure

A lower extremity exoskeleton structure is shown in Fig. 1(a), where four actuators are used to drive the hip and knee joints while the ankle joints are passive. Each actuator consists of a double-acting hydraulic cylinder and a servo valve.

To facilitate the presentation, the hip and knee joints on the right leg are defined as joints 1 and 2, and on the left leg 3 and 4 respectively. The hip joint angles \( \theta_i \) (\( i = 1, 3 \)) are measured as the positive counterclockwise displacement of the distal upper link from the torso link (zero in the standing position); while the knee joint angles \( \phi_i \) (\( i = 2, 4 \)) are measured as the positive clockwise displacement from the distal lower link from the upper link (zero in the standing position). The maximum payload is 40 kg (not including the power unit) and the maximum stride frequency is 1 Hz.

The right leg details are zoomed in, displayed in Fig. 1(b). Angle \( \phi_i \) changes as a function of \( \theta_i : \phi_i = -\theta_i - \phi_{i0} \), where \( \phi_{i0} \) is the initial value of \( \phi_i \) in standing position. \( l_{i0} \) is the cylinder initial length, \( D_i \) is the cylinder diameter and \( d_i \) is the rod diameter. So the displacement of the cylinder rod \( l_{ia} \) can be formulated as (1).

\[
I_{ia} = \left( \sqrt{\frac{l_{i0}^2}{4} + l_{i0}^2 - 2l_{i0}ic \cos \phi_i} - l_{i0} \right) i = 1, 2, 3, 4
\]

2.2. Pressure requirement

There are three main concerns in determining the system pressure, i.e. the load capacity, the compactness of the components, and the transmission efficiency, defined as the ratio of the power delivered to the actuators divided by the power produced by the hydraulic pump. On one hand, when a high pressure level is adopted, larger force could be exerted by a certain actuator, the hydraulic flow rate required by the system could be reduced, and components with smaller size, such as valves, actuators and hoses could be adopted. On the other hand, high system pressure results in more leakage in the pump and valves, thus reduces the transmission efficiency. High pressure also causes wear of the sealing parts, and increases the safety risk to the wearer of the exoskeleton.

As a result of the compromise between efficiency and compactness, the maximum system pressure is determined to be 9 MPa.

2.3. Flow rate requirement

2.3.1. Method

Flow rate requirement depends much on the stride frequency. An indirect method was used to calculate the flow rate without using a flowmeter. Based on the kinematics of the exoskeleton (1), the flow into each cylinder \( q_i \) can be calculated by (2), where \( v_{ia} \) is the velocity of the cylinder rod.

\[
q_i = \begin{cases} 
\frac{\pi}{4} \left( \frac{D^2}{4} - v_{ia} \right) & v_{ia} \geq 0 \\
-\frac{\pi}{4} \left( D^2 - d^2 \right) & v_{ia} < 0 
\end{cases}
\]

As the leakage of the pump used in the CHPU can be ignored when the maximum system pressure is 9 MPa, the leakage of the system mainly comes from the servo valves. The leakage of one
servo valve consists of static leakage that is proportional to the supply pressure $p_i$ and dynamic leakage that is proportional to the flow rate through the valve. Therefore the leakage $q_{vi}$ of an actuator (for joint $i$) is given in (3), where $k_{ls}=0.4$L/MPa/min is the static leakage coefficient and $k_{ld}=0.02$ is the dynamic leakage coefficient according to the specification of the servo valves. Ignoring the influence of the elements whose capacity changes with the system pressure, the flow rate required by the payload $q_l$ (all joint actuators) can be calculated by (4).

$$q_{vi} = k_{ls}p_i + k_{ld}q_i$$  \(3\)

$$q_l = \sum_{i=1}^{4} (q_i + q_{vi})$$  \(4\)

The Clinical Gait Analysis (CGA) data provides the information on how the joint angle changes when people are walking. The hip joint angle and knee joint angle in one walking cycle are showed in Fig. 2 [17]. Assuming that the system pressure is maintained as the maximum value, the flow rate requirement can be calculated by (4), in one walking cycle, the mean value and the peak value are most concerned. Considering the gait may have small changes during different stride frequencies and vary from person to person, a gait measure device was built by tying a lightweight artificial limb to the volunteers' lower limb. Angular transducers were installed to measure the joint angle. Three volunteers (aged 23–26 with about 175 mm height) were requested to walk two times in their own normal and fast walking speed, each time the volunteers walked more than five steps for averaging. Because the flow rate peak value from the volunteers' gait has fluctuation between steps, we only take the volunteers' flow rate mean value for reference.

2.3.2. Results

Fig. 3 shows the mean value and the peak value when people walking at different stride frequencies. The solid line and the dashed line come from the CGA data while the discrete points come from the volunteers.

Although different volunteers walked in different speeds, but the trend of the flow rate requirement is same with the data from CGA. The peak value of the flow rate requirement is much higher than the mean value, so an accumulator is necessary to help generate more flow rate. The rated flow rate should not be much larger than the requirement for a highly compact power unit because larger flow rate requires larger components. Since the maximum stride frequency of the exoskeleton is 1Hz and the corresponding mean value is 8.37LPM (liter per minute), so 9LPM rated flow rate can meet the flow rate requirement.

3. CHPU overview

3.1. Working principle

Fig. 4 shows the working principle of the CHPU. An IC engine (2) coaxially drives a pressure-compensated pump (6) and powers a generator (1) through a gear box (5). Clutch (4) realizes disengagement and engagement of the driving force from engine to pump and generator, which makes the engine easily started. High pressure hydraulic oil from the pump flows through a check valve (7) and a filter (12) then drives the cylinders. A spring pressurized reservoir (3) is used as the hydraulic tank to make the CHPU a closed system. Over high pressure is prevented by a relief valve (10) and system pressure (high and low) is measured by two pressure transducers (8) and (11). A diaphragm accumulator (9) with a gas pre-charge pressure of 6MPa is employed to provide the excessive flow rate for high frequency walking and to reduce the pressure fluctuation. Hydraulic system is cooled by a DC motor driven air cooling radiator (13). All the components (1)–(13) are integrated into a properly designed aluminum manifold. A high-frequency Hall sensor (SCL2-20K) is also integrated on the manifold to measure the engine speed. The key parameters of the CHPU are shown in Table 3.

3.2. Mechanical structures

Fig. 5 shows the physical layout of the CHPU. Components (1)–(13) have been shown in Fig. 4. The inlet (14) and outlet (15)
connected the exoskeleton robot through the hoses. A servo motor (16) was integrated for controlling the engine throttle opening. The air cooling radiator was located in the rightmost position to get enough space for the fresh air circulation. The engine was placed in the leftmost position so that the operator could commodiously start the engine by pulling the bracing wire. The bracing wire could be also extended to any suitable position by conversion devices such as a pulley. With a 450 mm length, 250 mm width and 290 mm height, CHPU could be easily integrated into many compact systems.

3.3. Prime mover

After comparing and tentatively using several engines, a two-stroke single cylinder IC engine (G320RC, ZENOAH) was employed as the prime mover. The engine produces 2.4 kw rated power at 13,000 rpm rated speed and weighs 2.3 kg including a muffler and a clutch. As an engine designed for the use of radio control car, G320RC has a high specific energy with high heat-sinking capability. Compare to the engine designed for model boat or model aircraft use, this engine does not need extra cooling water or air to cool the engine cylinder. At 10,000 rpm rated speed, the engine produces 2.08kw total power which is sufficient for the CHPU.

3.4. Pump

The high speed pressure-compensated pump has a rated displacement \( Q_p = 0.9 \, \text{ml/r} \), meanwhile, the rated speed \( n_p \) is 10,000 rpm and the compensated pressure \( p_r \) is 9 MPa. The high rated speed is close to the engine rated speed which leads to high utilization ratio of the engine power. The light weight (1 kg) and small size also makes the pump easily integrated into the manifold. The other outstanding advantage of the pump is energy saving. When the system pressure is higher than \( p_r \), the pump decreases its own displacement so the system pressure can be reduced and vice versa. In this way, energy waste and excessive heat due to the overflow is avoided. In addition, the displacement of the pump changes non-instantaneously so the load of engine changes non-instantaneously. Then the engine stall caused by the sudden increase of the load torque can be avoided.

3.5. Reservoir

A spring pressurized reservoir is brought forward as the tank of the CHPU. The rated boost pressure is 0.3 MPa and maximum capacity is 300 ml. Compared to the conventional hydraulic tank, a pressurized reservoir can easily supply the fluid to the pump inlet and prevent flow leakage, contamination or cavitation caused by all kinds of motions of the robot. Spring is a convenient and economical choice for pressurizing. Using a displacement sensor, the capacity and pressure of the reservoir can be easily measured. The reservoir was designed based on a graphical multi-objective optimization method [18] to balance several performance indicators such as pressurization, volume, mass and size. The reservoir length is 130 mm, diameter 75 mm and it weighs only 787 g. The compositions of the spring pressurized reservoir are shown in Fig. 6.

3.6. Generator

A Brush-less DC motor, which is essentially a type of 3-phase synchronous motor, is mounted on the gearbox, driven by the engine, and working as a 3-phase generator. A shield is used to protect the motor rotor as shown in Fig. 5. The type of the motor is 4240, which means the diameter is 42 mm and the axial length is 40 mm. The motor weighs 155 g. The short-circuit line current of 20A and open-circuit line voltage of 4.3 V is measured in test, when the engine is running at approximately 5000 rpm.

Several CHPU prototypes have been built for higher power density and better performance in other aspects such as dimension, cooling, noise, starting mode, etc. Obviously better elements lead to better systems. In the latest CHPU prototype, the air cooling radiator still takes up too much space even this radiator is the smallest one available to us. A new muffler is being developed to further reduce the noise.

4. Evaluation and models

4.1. Ragone plot analysis

Ragone plot is the general theory for energy storage devices providing the available energy of an energy storage device for constant active power request [19]. The specific energy \( \hat{E} \) and specific power \( \hat{P} \) is described in (5) as shown in [1].

\[
\hat{E} = \left[ \frac{1}{\eta} \left( 1 + \frac{1}{\beta} \right) \frac{M_C}{P_{\alpha}} \right]^{-1}
\]

\[
\hat{P} = \frac{\hat{E}}{t}
\]

Parameters \( \eta \) and \( M_C \) have been shown in Table 3. The specific energy of the fuel \( h \) is 44 MJ/kg and the constant \( \beta = 4 \) defined as the ratio of fuel mass to the mass of the fuel tank. Parameter \( t \) presents the operating time. The total output power \( P_{out} \) is 1.45 kw (the sum of \( P_B \) and \( P_E \)).

The Ragone plot analysis of the CHPU is shown in Fig. 7. When the working time grows up, the specific power becomes lower and the specific energy becomes higher and vice versa. The result
confirms that the CHPU maintains a high specific power over 10 hours working time or more.

4.2. CHPU models

As the power source of the exoskeleton robots, the model of the CHPU is built and parameters are identified.

It is usually hard to model an IC engine because of the complicated physical and chemical changes during the combustion cycle. In this paper, the engine model only reflects its torque-speed property for simplicity, rather than the intricate internal characteristics. The model of the engine has one output, the engine speed, which depends on two inputs: the throttle opening and the load torque. The engine driving torque \( T_d \) (Nm) changes as the function of the throttle opening \( \alpha \) (percentage from zero to one) and the engine speed \( n \) (rpm) or \( \omega \) (rad/s). The linearization of driving torque \( T_d^* \) in the adjacent of working point \((\alpha_0, \omega_0)\) is shown in (6).

\[
T_d^* = T_d(\alpha_0, \omega_0) + \frac{\partial T_d}{\partial \alpha} \Delta \alpha + \frac{\partial T_d}{\partial \omega} \Delta \omega
\]  

Whereas, as the input throttle opening can be controlled by the controller of the exoskeleton, the engine speed is determined by the coupling of the engine and the load. Therefore the throttle \( \alpha \) is taken as a given constant, so that \( T_d^* \) changes only as the function of \( \omega \). According to the speed characteristics of the gasoline engine and the specification of G320RC, the function \( T_d^*(\omega) \) is approximately written as (7). Assume that the parameter \( \frac{\partial T_d}{\partial \omega} \) is invariant when \( \omega \) changes in a certain range.

\[
T_d = T_d(\omega_0) + \frac{\partial T_d}{\partial \omega} (\omega - \omega_0)
\]  

The dynamic characteristic of the engine is shown in (8). Where \( J \) (kgm²) is the equivalent moment of the load inertia, \( T \) (Nm) is the load torque and \( c \) (Nms/rad) is the load damping.

\[
\dot{\omega} = T_d - T - c \dot{\omega}
\]  

Combining (7) and (8) we can describe the dynamic characteristic of the engine as (9), where \( c_e \) is the equivalent damping that indicates the torque variation caused by the speed. The characteristic of the pump, as introduced previously, is formulated as (10).

Where \( q \) (LPM) is the output flow rate of the pump, \( Q \) (ml/r) is the actual displacement of the pump, \( p_i \) (MPa) is the system pressure. \( K_p \) (mlr/MPa) specifies the pressure-compensation characteristics of the pump.

\[
\dot{p} = T_e - T - c_e \omega
\]

\[
c_e = c - \frac{\partial T_d}{\partial n} T_e = T_d(\omega_0) - \frac{\partial T_d}{\partial \omega} \omega_0
\]

\[
Q(p_i) = \begin{cases} Q_l, & p_i \leq p_r \\ Q_l - K_p(p_i - p_r), & p_i > p_r \end{cases}
\]

\[
q = nQ(p_i)
\]

The entire system model, (7)–(10), can be expressed as Fig. 8. When the system pressure is lower than \( p_r \), the displacement of the pump is constant and the system is linear. However when the system pressure is higher than \( p_r \), the displacement of the pump changes along with the system pressure. The transfer function in the case when \( p_i > p_r \), contains nonlinear components.

4.3. Parameters identification

Least square method is a useful tool for identifying parameters of a “gray box” [20]. In the CHPU model, parameters \( J, c_e \) and \( T_e \) are unknown. The engine model can be written in the matrix form as (11), where the matrix \( H \) and \( C \) are shown in (12).

\[
T = HC
\]

\[
H = \begin{bmatrix} -J \\ -c_e/T_e \end{bmatrix}
\]

In the experiments, using the pressure sensor and the speed sensor, the system pressure and the engine speed can be measured and \( \omega(k) \) and \( T(k) \) can be calculated according to Eq. (13). Therefore, based on the least square method, the matrix \( C \) can be written as (14) and the parameters can be estimated.

\[
\omega = \frac{2\pi n}{60}
\]

\[
T = \frac{P_i Q}{2\pi}
\]

\[
C = (HH^T)^{-1}H^Ty
\]

\[
H = \begin{bmatrix} \dot{\omega}(1)\omega(1) \\ \dot{\omega}(2)\omega(2) \\ \vdots \\ \dot{\omega}(K)\omega(K) \end{bmatrix}, y = \begin{bmatrix} T(1) \\ T(2) \\ \vdots \\ T(K) \end{bmatrix}
\]

5. Tests and discussion

The CHPU prototype was tested on the lower extremity exoskeleton robot fixed on a height-adjustable bench, as shown in Fig. 9. Hoses were used to connect the CHPU and the actuators. The displacement sensors were installed on the hydraulic cylinders. In the tests, the CHPU drove the robot to track the gait from the CGA data at different stride frequencies in the closed loop, where proportional control was adopted for simplicity. The sensors measured and recorded at 100 Hz frequency.

5.1. Flow estimation method verification

In test one, the engine throttle was set to a small value to ensure the system pressure below 6 MPa, so that the displacement of the pump was static and the accumulator did not consume or provide hydraulic flow. In this condition the flow rate from the pump \( q_p \) could be calculated by (15). With the engine speed \( n \), the
system pressure $p_i$ and the displacement of every cylinder $l_i$ being measured, it is possible to validate the flow rate estimation (4) by comparing $q_i$ and $q_p$, as shown in Fig. 10(a).

$$q_p = Q_r n \tag{15}$$

The $q_i$ and $q_p$ match well except for some errors especially at the peaks and valleys of curves. As can be noticed, there are elastic elements connecting the pump and the actuators such as the hoses, whose volume changes with the system pressure. The chamber elasticity could explain the flow rate error. The equivalent flow rate caused by the elasticity $q_e$ is formulated as (16), where $k_e$ is the elastic coefficient. The comparison of $q_e - q_i$ and $q_e$ is shown in Fig. 10(b), where $k_e = 25$ L/MPa is estimated. This comparison confirms that the difference between $q_i$ and $q_p$ is mainly caused by the chamber elasticity and the flow rate output of the CHPU can be calculated as $q_i$.

$$q_e = k_e \frac{dp_i}{dt} \tag{16}$$

5.2. CHPU model verification

The test two was designed to verify the CHPU model, engine speed and system pressure were acquainted twice in test 2-A and test 2-B as shown in Fig. 11. In the two tests, the throttle opening was both 0.27 and the stride frequency was both 0.5 Hz, while there are some time-varying experimental conditions such as the temperature, load damping and the ingredient of the fuel, etc.

The physical parameters were identified based on the least square method (14) and the result is shown in Table 4. With the parameters identified and the system pressure measurement treated as the input, the engine speed can be calculated by the transfer function. Fig. 12 shows the comparison of the engine speed between the calculation and measurement.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$J$</th>
<th>$c_e$</th>
<th>$T_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result of test 2-A</td>
<td>0.000115</td>
<td>0.000506</td>
<td>0.7551</td>
</tr>
<tr>
<td>Result of test 2-B</td>
<td>0.000105</td>
<td>0.000461</td>
<td>0.8575</td>
</tr>
</tbody>
</table>

The identification results of $J$ in the two experiments are close and so do the results of $c_e$. The small fluctuations of the results are mainly caused by the time-varying experimental conditions mentioned above. The value of parameter $T_e$ is different because the initial value of the engine speed is not the same. In the application, the parameters will be updated by real time identification regularly.

The predicted engine speed conforms to the measurement as shown in Fig. 12, indicating that the CHPU model represents the dynamic characteristics of the physical prototype. With parameters identified at multiple throttle opening levels, the CHPU model can
be used to predict the performance of the system and design the controller.

For further verification of the identification method, using the average of the obtained \( J \) and \( c_r \), that is, \( J_f = 0.000110 \) and \( c_r = 0.0004845 \), while parameter \( T_e \) remains unchanged: 0.7551 for test 2-A and 0.8575 for test 2-B. Taking the system pressure in the two tests as the input, and the engine speed can be calculated again as shown in Fig. 13. The error in Fig. 13 is slightly larger than in Fig. 12, but the predicted engine speed still conforms to the measurement.

5.3. CHPU prototype output

In test three, the reference movement of each joint was generated from the CGA data with stride frequency 1.1 Hz, the throttle opening was elevated (approximately 73%) to boost the engine power, in order to evaluate the CHPU output capacity. Fig. 14 demonstrates the system pressure at the pump outlet, as well as the CHPU output flow rate estimated by (4).

The maximum payload flow rate (13LPM) is much higher than the average flow rate (8LPM) confirming the important role of the accumulator. The average flow rate is less than the theoretical value (9LPM) and this is because the reference movements were not precisely tracked due to the control method in the test. The system pressure is steady in a range from 8.4 MPa to 9.4 MPa with the help of the pressure-compensated pump and the accumulator, indicating that the CHPU could work reliably when the robot makes relatively quick movements. The high frequency dithering of the pressure could be noticed, which is caused by the pump.

6. Conclusion

A novel compact hydraulic power unit powered by an internal combustion engine (named CHPU) is brought forward in this paper. The CHPU provides a 1.5 kw hydraulic power and 100 w electric power, whereas the weight is only 16.6 kg. Ragone plot analysis indicates the CHPU can keep a high specific power over 10 hours working time or more.

The development progress of the CHPU is also presented and the advantages of using a high speed pressure-compensated pump and a spring pressurized reservoir are highlighted. In the progress, an indirect method is used to calculate the flow rate of the payload based on the displacement of the actuators.

The CHPU model has been built to analyze the dynamic characteristic of the power unit. Based on the simplified engine model whose physical parameters are identified by the least square method, the relationship between the load pressure and the flow rate output of the pump is revealed.

Tests are carried out on the CHPU prototype. The flow rate comparisons between the test and the calculation verify the accuracy of the indirect method. The identification results and the engine speed prediction results demonstrate the CHPU model can describe the system dynamic characteristics. The results of the payload flow rate and the system pressure at 1.1 Hz stride frequency confirm the CHPU output capacity.

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No.51275450), National Basic Research Program of China (973) (Grant No. 2014CB046403), and Science Fund for Creative Research Groups of National Natural Science Foundation of China (Grant No. 51521064).

References


