Systematic method for selection of motor-reducer units to power a lower-body robotic exoskeleton

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Powered exoskeletons are wearable robotic devices intended to provide extra power to ailing limbs during walking. The selection of appropriate motor and transmission is essential in enhancing the power-to-weight ratio of the system while keeping the cost down. This article presents a systematic method to size the motor-transmission unit by taking into account the motor’s characteristics, transmission inertia, efficiency and cost of the system. Since a lower-limb exoskeleton system is designed for walking, clinical gait analysis data is used to assess the dynamic load requirements. An optimal selection of the motor and gearhead is made to power the hip joint of the exoskeleton. Choice of the motor-reducer unit is compared using different criteria such as maximizing load acceleration or peak power. The framework can be easily extended to other joints as well as to other types of exoskeletons.

**Keywords:** Rehabilitation robotics; Motor sizing; Transmission selection; Assistive robots.

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1. Introduction

Exoskeletons are advanced electromechanical systems that externally attach to a human body to provide support and strength. The structure is equipped with sensors to predict human intention while actuators provide support to the limb. The past two decades have seen exponential growth in research in this area. Several lower-body exoskeletons have been developed for medical rehabilitation and gait therapy of paraplegic and stroke population. Examples include HAL (Hybrid Assistive Limb) [1], ReWalk [2], and Lokomat [3], to name a few. Robotic exoskeletons are gaining attention in Pakistan as well where a few labs have started to develop exoskeletons of their own [4–6].

Most exoskeleton systems can be classified into two categories, 1) the self-contained personal devices intended for outdoor use (e.g. ReWalk), 2) treadmill-based rehabilitation systems for use in clinical settings (e.g. Lokomat). While the former suffer from some major limitations such as self-balancing, weight and cost, the treadmill-based systems are gaining popularity in the rehabilitation centers worldwide for automated patient therapy.

The overarching goal of this research is to develop a personal exoskeleton device for the paraplegic population in Pakistan. In this regard, ReLEx (short for Reconfigurable Leg Exoskeleton) is a lower-body exoskeleton platform currently under development (c.f. Fig. 1a). The system consists of an off-board actuation system with a power transmission system and an overhead harness for safety. A set of 4 powerful AC motors drive the human-exoskeleton system at the hip and knee joints.

The strength of this setup lies in the decoupling of the exoskeleton structure from the actuation system. This way, exoskeletons of different sizes and shapes can be quickly tested without having to redesign the actuation system. This will speed-up the design process allowing rapid human-in-the-loop simulations early in the design process. In addition, off-board actuation results in a relatively uncluttered environment around the body which is
helpful during the gait analysis using vision-based motion capture systems. Lastly, the choice of flexible Bowden cable permits out-of-treadmill operation of the system which is not possible with the similar commercial systems.”

The selection of motors along with the optimal gear reducer is crucial in all mechatronic systems. A majority of robotic exoskeletons employ electric motor to power the joint. A larger-than-necessary motor and gearbox set would result in bulky systems at a higher cost. Similarly, an inferior choice could result in limited device functionality. Hence, it is critical for powered exoskeletons to make an informed choice to minimize the power-to-weight ratio. Conventional wisdom in robotics favors smaller motors with larger transmissions (gearboxes), mounted near the physical joint [7, 8]. However, this may be counterproductive as smaller motors tend to have larger electrical losses. Moreover, larger gearboxes are bulkier and less efficient owing to multiple stages of reduction. Hence a balance must be struck between the size of motor and gearbox keeping in view multiple factors.

There are several empirical and analytical methods in the literature to make an informed decision on this selection. A classical inertia matching method between the motor and load was proposed by Pasch and Seering [9]. It assumes a purely inertial load and no losses in the transmission, which is seldom the case in real-life applications. Similarly, in [10, 11], the authors presented a procedure for the selection of servo motors for a generic load. Their methodology produces a chart for all feasible motors and corresponding transmission ratio ranges. However, as we shall demonstrate in later sections, these methods often result in superficial transmission ratio ranges which are not possible to achieve or obtain commercially.

A more sophisticated approach is taken by others [12, 13] who introduce load characteristics in the selection process. A simple criterion is developed as a result to estimate if a motor can run a given inertial load. However, their method does not attempt to incorporate any optimality criterion. Similarly, other authors have attempted to size the motor-transmission using dynamic simulations approach [14]. This approach requires comprehensive modeling of the whole system. Hence, this approach is not only time-consuming but also somewhat unnecessary at such an early stage of the selection process.

In this article, we take a simpler yet powerful approach. We integrate the law of motion of the system in the selection process but without performing the complex simulations. This is achieved by using a simplified model of the system taking into account the transmission losses and gear ratio inside the motion equations. Moreover, we seek to optimize our selection from the off-the-shelf available motor and gear sets.

The selection process consists of 3 steps:
1. Select a set of candidate motors and all of the compatible, commercially available gearboxes.
2. Evaluate each motor-gearbox combination and eliminate those which would be unable to run the load at the designed torque and speed.
3. Of all the feasible combinations, perform optimality calculations and make the final selection based on stipulated optimality criterion such as peak power, energy efficiency, etc.

Since the ReLEx exoskeleton is designed to perform periodic walking, the desired motion trajectories may be taken from the human gait data in the biomechanics literature. Similarly, the motor and transmission characteristics are available from their respective datasheets.
In the following sections, this method is applied to the selection of the motor-transmission unit to power the hip joint only. The framework applies to all other joints of lower-body or any other exoskeleton system. The article is organized as follows: Section 2 presents the model of the system and the development of selection criteria. Section 3 summarizes the selection procedure using this method. Section 4 presents the results for a selection of commercially available motor and gearbox units. Section 5 concludes the article.

2. Theory and formula

2.1. System Modeling

A lumped-element model of the system is derived as shown in Fig. 2. It consists of the motor, gearbox and leg modeled as rotary inertial loads. The human leg is considered passive and is to be completely driven by the motor. The gear ratio \( \eta \) is defined as,

\[
\eta = \frac{N_1}{N_2} = \frac{\omega_f}{\omega_m} = \frac{\theta_l}{\theta_m}
\]

Where \( N_1 \) is the number of gear teeth on the motor side.

The basic equation of the motion of the system can be written as:

\[
T_m(t) = (J_m + J_g)\ddot{\theta}_l + \frac{n}{\eta_g} J_l\ddot{\theta}_l
\]

Where \( T_m \) is the required motor torque to drive the required load profile, \( J_l\ddot{\theta}_l \). This equation also incorporates the gearbox characteristics as its reduction ratio, inertia, and efficiency.

![Fig. 2. The model of the system including rotor, gearbox and load inertias.](image)

From (1), \( n = \eta \theta_m \)

Hence \( T_m \) can be rewritten as:

\[
T_m = \frac{1}{n} (J_m + J_g)\ddot{\theta}_l + \frac{n}{\eta_g} T_l(t)
\]

which represents motor torque as a function of load characteristics.

For the selection of motors and gearboxes, the root mean square (RMS) and peak values of the required motor torque are of interest. The RMS motor torque expression can be deduced from (3):

\[
(T_m)_{RMS} = \sqrt{\frac{1}{T} \int_0^T \left( \frac{1}{n}(J_m + J_g)\ddot{\theta}_l + \frac{n}{\eta_g} T_l(t) \right)^2 dt}
\]

(4)

Similarly, the peak torque expression can be written as:

\[
(T_m)_{PEAK} = \max \left| \frac{1}{n} (J_m + J_g)\ddot{\theta}_l + \frac{n}{\eta_g} T_l(t) \right|
\]

(5)

For a particular catalog motor to be able to run the load, the rated and maximum torque values of the motor should be above RMS and peak motor values deduced above. This is to say,

\[
T_{\text{rated}} \geq (T_m)_{RMS}
\]

(6)

\[
T_{\text{max}} \geq (T_m)_{PEAK}
\]

(7)

2.2. Power and Energy Calculations

The power and energy consumption are also important factors while choosing a motor-gearbox unit. In our model, the power generated by the motor to run the load is written as:

\[
P_{\text{mech}} = \frac{1}{n^2} (J_m + J_g)^2 \ddot{\theta}_l \dot{\theta}_l + \frac{1}{\eta_g} T_l \dot{\theta}_l
\]

(8)

The electrical losses within the motor can be modeled as:

\[
P_{\text{loss}} = R_m I_m^2
\]

The total power requirement of the motor is the sum of mechanical power to run the load and the power lost, hence:

\[
P_m = P_{\text{mech}} + P_{\text{loss}}
\]

(9)

Lastly, the energy consumed per cycle may be calculated by integrating the net power generated over time:

\[
E = \int_0^T P_m dt
\]

(10)
Table 1. Nomenclature.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{rated}}$</td>
<td>Rated motor torque from catalog</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>Peak motor torque from catalog</td>
</tr>
<tr>
<td>$J_m$</td>
<td>Motor rotor inertia</td>
</tr>
<tr>
<td>$J_l$</td>
<td>Load inertia (exoskeleton + human leg)</td>
</tr>
<tr>
<td>$\ddot{\theta}_l$</td>
<td>Angular acceleration of the load</td>
</tr>
<tr>
<td>$T_l$</td>
<td>Load torque</td>
</tr>
<tr>
<td>$n$</td>
<td>Gear ratio</td>
</tr>
<tr>
<td>$\eta_g$</td>
<td>Gearhead efficiency</td>
</tr>
<tr>
<td>$T$</td>
<td>Total cycle time</td>
</tr>
<tr>
<td>$R_m$</td>
<td>Motor winding resistance</td>
</tr>
<tr>
<td>$k_c$</td>
<td>Motor torque constant</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Motor torque to drive the load</td>
</tr>
<tr>
<td>$N_{1}, N_{2}$</td>
<td>Number of gear teeth on the motor and load sides respectively</td>
</tr>
<tr>
<td>$\theta_m, \omega_m$</td>
<td>Instantaneous angular position and angular velocity of the motor shaft</td>
</tr>
<tr>
<td>$\theta_l, \omega_l$</td>
<td>Instantaneous angular position and angular velocity of the load</td>
</tr>
<tr>
<td>$\omega_{m, \text{max}}, \omega_{g, \text{max}}$</td>
<td>Maximum speed limits for the motor and gearbox reported by the manufacturer</td>
</tr>
<tr>
<td>$\omega_{m, \text{max}}$</td>
<td>Peak angular velocity value in the load profile</td>
</tr>
<tr>
<td>$n_{\text{lim}}$</td>
<td>Maximum acceptable gear ratio for a particular motor-gearbox combination</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Required motor torque to run the load</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Total power requirement of the motor to run the load</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy consumed per cycle by the motor</td>
</tr>
</tbody>
</table>

2.3. Optimizing Gear Ratio
The first estimation of an ‘optimal’ gear reduction ratio may be obtained from the equation of motion of the system itself. From (3), we can deduce an expression for load acceleration as:

$$\ddot{\theta}_l = \frac{nT_m}{(J_m + J_g + \frac{n^2}{\eta_g} J_l)} - nT_m \frac{2n}{\eta_g} = 0$$

(11)

Gear ratio $n^*$ which maximizes load acceleration can be obtained by differentiation as:

$$\frac{\ddot{\theta}_l}{\eta_g} = 0$$

$$\left( J_m + J_g + \frac{n^2}{\eta_g} J_l \right) (T_m) - nT_m \left( \frac{2n}{\eta_g} J_l \right) = 0$$

This results in the optimal gear ratio of:

$$n^* = \sqrt[2]{J_m + J_g \frac{2n}{\eta_g}}$$

(12)

Note that this expression only involves the inertias of all three components disregarding the load torque or acceleration profile.

2.4. Estimation of Load Profile
During a human gait cycle, each leg periodically switches from stance to swing phase. The stance phase comprises of 60% of the gait cycle during which the foot stays on the ground and propels the body forward. The rest of the cycle comprises the swing phase [15]. In the exoskeletons designed for the paraplegic population, the motors have to provide all the power to execute the walking cycle without any contribution from the user. Hence, the kinematics and dynamics of the leg during a normal gait cycle constitutes the load on the motors. The load profile for this study is taken from human clinical gait analysis (CGA) data. The most widely used dataset for this purpose was collected by [16] for young adults (56.7 kg, 1.35 m height) at a pace of around 1.39 m/s. Since our exoskeleton system is designed for older adults, the velocity, acceleration and torque profiles from this dataset are scaled up for 100 kg mass and 1.8 m height using the method proposed by [17]. The resulting torque and velocity profiles for the thigh (hip) segment are shown in Fig. 3.

2.5. Maximum Allowable Reduction Ratio
Looking at the desired velocity profile of the load (dotted line in Fig. 3), we can observe that the peak leg velocity which should be achieved post gear-reduction is around 170 deg/s. Since each motor and gearbox has a maximum speed limit, we can work out a limiting reduction ratio $n_{\text{lim}}$
Fig. 3. Hip torque and angular velocity profile taken from the literature [16] and scaled for 100kg total mass of the human-exoskeleton system. The torque profiles constitute the load profile $T_l$ in (3).

as:

$$n_{lim} = \frac{\omega_{l,max}}{\min(\omega_{m,max}, \omega_{g,max})}$$

Expression (13) gives the maximum acceptable reduction ratio for a specific motor-gearbox combination, hence the following condition must hold for the off-the-shelf gearbox selection:

$$n \leq n_{lim}$$

(14)

3. Selection Procedure

There are several commercial vendors for the provision of motors and gearbox systems. Since ReLEx is designed for indoor use and would require steady high torques, AC synchronous motors are chosen. 8 industrial-grade candidate motors from 2 vendors (Delta Electronics and Glentek Inc.) ranging from 100 W to 1000 W power rating are selected for the analysis. Motors from other manufacturers in this power range have also similar torque and speed characteristics. Hence, the selection made during our analysis here can be extended to select similar motors from other manufacturers. Characteristics of the selected motors are given in Table 5 of the appendix.

Similarly, a compatible planetary gearhead series is selected from Delta Engineering with a reduction ratio from 10 to 100 (largest off-the-shelf available ratio). The gearhead parameters as reported by the manufacturer are given in Table 6.

3.1. Workflow

Using the equations developed above, an efficient workflow is adopted to choose optimal actuation for this system. It starts with the selection of candidate motors and their compatible set of gearboxes. Then, for all combinations of motors and gearboxes, the criterion described in (14) is checked and any combination which does not satisfy this condition is discarded for further analysis. Next, the criteria in (6) and (7) are tested to see if the combination would be able to run the load or not. This is the most important feasibility test which readily eliminates the undesired combination.

In the next step, of all feasible combinations, the optimal gear reduction is pursued. For this purpose, one such criterion was developed in (12). Similarly, power and energy criteria were developed in (9) and (10). These criteria provide a set of optimal combinations which may be further analyzed in terms of cost and space limitations to make a final decision. We demonstrate the application of this strategy in Section 4.

4. Result discussions

4.1. Feasibility Checks

As outlined above, the first step in the selection process is to check the feasibility of the candidate motors and gearhead to run the load. Since there are 8 motors and 10 gearbox sets in our selection, it makes a total of 80 motor-gearbox combinations. We first test the criterion described in (14) to eliminate any gearboxes from the set which will limit the load speed below the required. For this purpose, a maximum allowable reduction ratio is calculated using (13). This results in value of 1:173 for the 5 motors by Delta Electronics and 1:138 for the remaining 3 motors from Glentek Inc. These values represent an upper-bound on the gear ratio to achieve the designed load velocity with the selected motor. As both these values are comfortably above the maximum reduction ratios available in the selected gearbox series (1:10 to 1:100), all these gearboxes are feasible to drive the load at the designed speed.

Table 2 summarizes the results against criteria (6) and (7) for all combinations in Table 2. 46 out of 80 combinations fulfill the criteria. Interestingly, the motor with the smallest rated torque of 0.32 Nm cannot drive the load with any of the available gear ratios. As the motors get bigger, the number of feasible gearboxes increases. The largest motors (ECMA-C1010 and GMB3530-48) can drive the load with all transmission ratios above 1:15.

In other words, this application of criteria in (6) and (7) indicate an upper-bound on the gear ratio to achieve
Table 2. Feasibility result for all selected motors against all gear ratios. The combinations which fulfill the criterion (6) and (7) are marked with ‘×’. Empty fields indicate non-compliance. Out of the total 80 combinations, only 46 are deemed feasible.

<table>
<thead>
<tr>
<th>Motor Model</th>
<th>Rated torque Nm</th>
<th>Gearbox series, PA100-AxxxxE2255</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=1:10</td>
<td>n=1:15</td>
</tr>
<tr>
<td>ECMA-C0401</td>
<td>0.32</td>
<td>x</td>
</tr>
<tr>
<td>ECMA-C0602</td>
<td>0.64</td>
<td>x</td>
</tr>
<tr>
<td>ECMA-C0604</td>
<td>1.27</td>
<td>x</td>
</tr>
<tr>
<td>ECMA-C0807</td>
<td>2.39</td>
<td>x</td>
</tr>
<tr>
<td>ECMA-C1010</td>
<td>3.18</td>
<td>x</td>
</tr>
<tr>
<td>GMB2030-28</td>
<td>1.50</td>
<td>x</td>
</tr>
<tr>
<td>GMB3515-23</td>
<td>1.81</td>
<td>x</td>
</tr>
<tr>
<td>GMB3530-48</td>
<td>3.39</td>
<td>x</td>
</tr>
</tbody>
</table>

The designed load torque. Together with the upper-bound calculated above, the feasibility results can be summarized in Fig. 4.

Fig. 4. Summary of feasibility test. For each motor, the vertical bar shows the feasible range of gear ratios to provide designed speed and torque at the load.

4.2. Optimization

Once all the feasible motor-gearbox combinations have been found, the next step is to find the best among them. An expression for the optimal gear ratio was found in (12) maximizing the load acceleration. Using this expression, an optimal ratio can be found for all 8 motors. The values are also compared to the classical inertial matching method \((\sqrt{J_m/J_l})\) by [9] and are reported in Table 3.

All in all, these methods favor very large reduction ratios. Especially, the ratios obtained by simple inertial matching suggest reductions of 1:1356 and 1:700 for smaller motors. Incorporation of gearbox inertia and efficiency in (12) results in more rational values but still are above the feasible threshold for most cases (c.f. Fig. 4). It means that if any of these motor-gearhead combinations is chosen, it will not be able to run the joint to the designed velocity (except for ECMA-C1010 where \(n^* < n_{lim}\)).

In short, despite involving a certain degree of optimality, the gear ratios proposed by these methods are impractical. This is partly because the complications of larger gearheads (bulkiness, losses, backlash, etc.) are not modeled in these estimates.

4.3. Peak power and Energy

Peak power and energy consumption of the motor are a measure of the cost and efficiency of the system. The motor generates power to drive the load while compensating for the losses in the system. A large part of the losses in motors consists of electrical losses which are modeled in (8) whereas the net power at each instant of time is calculated using (9). The peak of the net power determines the size of the associated drive electronics. Similarly, (10) calculates the energy consumed during one gait cycle by the motor. For each feasible motor-gearhead selection, these parameters are plotted against the gearhead ratios as shown in Fig. 5.

As can be observed, the curves for different motors show a similar trend for both criteria. For the GMB series motors, the peak net power requirement is generally very high, especially for smaller motors and for small reduction ratios. This is mainly due to the high winding resistance for these motors leading to large electrical losses (see table 5). Hence for this series, the highest gear reduction ratio of 1:100 seems to minimize the peak power as well as the energy consumed per cycle.

For the 4 motors in the ECMA series, there exists a trade-off between the motor and gearbox size. Larger motors (C0807 and C1010) tend to minimize the peak power and
Table 3.: The ‘optimal’ gear ratios found using classical methods and (12) developed above against each candidate motor. (Even though the model ECMA-C0401 has been eliminated in the previous step, it is included in this table only for comparison.).

<table>
<thead>
<tr>
<th>Motor Model</th>
<th>Optimal gear ratio ( \eta^* ) from (12)</th>
<th>Gear ratio using inertia matching method [9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMA-C0401</td>
<td>1:415</td>
<td>1:1356</td>
</tr>
<tr>
<td>ECMA-C0602</td>
<td>1:359</td>
<td>1:622</td>
</tr>
<tr>
<td>ECMA-C0604</td>
<td>1:330</td>
<td>1:495</td>
</tr>
<tr>
<td>ECMA-C0807</td>
<td>1:220</td>
<td>1:250</td>
</tr>
<tr>
<td>ECMA-C1010</td>
<td>1:144</td>
<td>1:148</td>
</tr>
<tr>
<td>GMB2030-28</td>
<td>1:372</td>
<td>1:700</td>
</tr>
<tr>
<td>GMB3515-23</td>
<td>1:268</td>
<td>1:331</td>
</tr>
<tr>
<td>GMB3530-48</td>
<td>1:224</td>
<td>1:255</td>
</tr>
</tbody>
</table>

Fig. 5. The peak power and energy consumed per cycle for each motor against the available gear reduction ratios. The arrows indicate the global minima or minimum point for a specific motor as summarized in Table 4.

energy consumption at relatively small gear ratios (1:30 to 50) while smaller motors (e.g. C0602) tend to achieve a minimum at around 1:70.

5. Conclusion

This analysis enables us to make a final selection that may depend upon a single or a combination of criteria. Some of these criteria are summarized in Table 4. If the space for mounting the motor-transmission unit is limited, the smaller ECMA-C0602 motor with a gear ratio of 1:70 could be used. If energy efficiency is of the highest importance, the larger motors (0807 or 1010) should be used with gearheads of 1:35 or 1:50 reduction ratios. This choice could also reduce the cost of associated electronics due to its less peak power value. In the context of the ReLEx platform, ECMA-C0602 is chosen with a gear reduction of 1:100 to power the hip joint. This choice results in a compact actuation system while keeping excess torque capacity for future up-gradation.

The framework presented in this article can find the optimal motor-gearhead combination to power the joints of a robotic exoskeleton, or any other articulated robotic system for this purpose. The strength of the method lies in the consideration of gearhead inertia and efficiency in the analysis right from the start unlike other methods in the literature. These parameters make a large impact on the optimality as seen in Table 2 when compared against the classical approach. The technique only considers commercially available actuators and gearheads and eliminates any all non-feasible combinations in the very first step. Moreover, the load profile is also fully integrated into the equations giving a realistic estimation according to the application.

In the future, we intend to extend this analysis to other joints of the exoskeleton. Moreover, mechanical losses along the transmission or post gear-reduction will be integrated to make the selection process more accurate. The heat produced in the motor would also be analyzed to estimate the heat dissipation requirements.

6. Acknowledgements

This work is supported by the National Center of Robotics and Automation (NCRA), Pakistan.
Table 4. Summary of results obtained for the hip joint actuation of the exoskeleton.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Criterion</th>
<th>Motor</th>
<th>Gearbox ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Smallest motor / Least combined weight (motor+gearbox)</td>
<td>ECMA-C0602</td>
<td>≥ 70</td>
</tr>
<tr>
<td>2</td>
<td>Most energy-efficient motor</td>
<td>ECMA-C0807</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Or</td>
<td>Or</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Least peak power requirement/ Smallest gearbox</td>
<td>ECMA-C1010</td>
<td>30</td>
</tr>
</tbody>
</table>

7. Appendix

Table 5. Selected motor specifications [18].

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Motor model</th>
<th>Rated torque (Nm)</th>
<th>Rated power (W)</th>
<th>Rated speed (rpm)</th>
<th>Max speed (rpm)</th>
<th>Winding resistance (ohm)</th>
<th>Torque const. (Nm/A)</th>
<th>Mass (Kg)</th>
<th>Motor rotor inertia (kg-m²)*10⁻⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ECMA-C0401</td>
<td>0.32</td>
<td>100</td>
<td>3000</td>
<td>5000</td>
<td>9.3</td>
<td>0.36</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>ECMA-C0602</td>
<td>0.64</td>
<td>200</td>
<td>3000</td>
<td>5000</td>
<td>2.79</td>
<td>0.41</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>ECMA-C0604</td>
<td>1.27</td>
<td>400</td>
<td>3000</td>
<td>5000</td>
<td>1.55</td>
<td>0.49</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>ECMA-C0807</td>
<td>2.39</td>
<td>750</td>
<td>3000</td>
<td>5000</td>
<td>0.42</td>
<td>0.47</td>
<td>3.8</td>
<td>11.8</td>
</tr>
<tr>
<td>5</td>
<td>ECMA-C1010</td>
<td>3.18</td>
<td>1000</td>
<td>3000</td>
<td>5000</td>
<td>0.2</td>
<td>0.44</td>
<td>4.7</td>
<td>33.3</td>
</tr>
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<td>6</td>
<td>GMB2030-28</td>
<td>1.50</td>
<td>490</td>
<td>4000</td>
<td>5000</td>
<td>5.4</td>
<td>0.36</td>
<td>3.1</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>GMB3515-23</td>
<td>1.81</td>
<td>610</td>
<td>4000</td>
<td>5000</td>
<td>1.3</td>
<td>0.29</td>
<td>3.8</td>
<td>6.7</td>
</tr>
<tr>
<td>8</td>
<td>GMB3530-48</td>
<td>3.39</td>
<td>910</td>
<td>3200</td>
<td>4000</td>
<td>2.5</td>
<td>0.61</td>
<td>5.4</td>
<td>11.3</td>
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</tbody>
</table>
### Table 6. Compatible gearhead series.

<table>
<thead>
<tr>
<th>Series model</th>
<th>Motor rated power (W)</th>
<th>Ratios</th>
<th>Efficiency</th>
<th>Maximum input speed (rpm)</th>
<th>Inertia (kg-m²)*10⁻⁵</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA100-AxxxxE2255</td>
<td>300W, 500W, 600W, 800W, 900W, 1kW, 1.3kW, 1.5kW, 1.8kW, 2kW</td>
<td>10, 15, 20, 25, 30, 35, 40, 50, 70, 100</td>
<td>&gt;97 for n=1:10 &gt;95 for the rest</td>
<td>5000</td>
<td>4.5</td>
<td>3.76 for 1:10</td>
</tr>
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<td></td>
<td>5.92 for the rest</td>
</tr>
</tbody>
</table>

### References


