Speed Control of Marine Diesel Engines Using Fuzzy Gain Scheduling
2002年 6月 22日

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Speed Control of Marine Diesel Engines Using
Fuzzy Gain Scheduling

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Abstract

In marine transportation, one of the most important factors is the energy saving. In order to reduce the fuel oil consumption, ship’s propulsion efficiency must be increased as much as possible. The propulsion efficiency depends upon a combination of an engine and a propeller. This situation led the engine manufacturers to design the engine that has lower speed, longer stroke and a small number of cylinders. Consequently, the variations of rotational torque became larger than before because of the longer time delay in fuel oil injection process and increased output per cylinder. As these new trends the conventional mechanical hydraulic governors for engine speed control have been replaced by digital governors which adopt the PID control or the optimal control algorithm. And the conventional PID controller has been extensively used to speed control of marine diesel engines. However, one of drawbacks is
that its control performance can be degraded if the parameters are fixed on whole operating points.

In this paper, a scheme for integrating PID control and the fuzzy technique is presented to control speed of a marine diesel engine on overall operating points. At first, the local PID controller is designed at each speed mode, whose parameters are optimally adjusted using a genetic algorithm. Then, fuzzy “if-then” rules combine the local controllers as a consequence part. To demonstrate the effectiveness of the proposed fuzzy PID controller, a set of simulation works on a marine diesel engine are carried out.
1 パート

PID制御の調整時に重要なパラメータであるPIDの調整方法について説明します。PIDパラメータの調整方法には、Ziegler-Nichols法、Cohen-Coon法等があります。さらに、自動調整方式（Autotuning）[3,4]、整数制御器（Intelligent controller）[5]、ファジー制御器（Fuzzy controller）[5]も紹介します。PID制御器の調整には、ファジー自調整（Fuzzy Self-Tuning: FST）[7-10]等も利用されます。
viii
·ÐÀ» ³»¸°´Ù.
2. データの形状の解析

2.1 データの形状の解析

[15-16].
Fig. 2.1 Block diagram of a marine diesel engine

![Block diagram of a marine diesel engine](image)

\[ Y(s) = \frac{K_a K_c K_r e^{-Ls}}{(1 + T_a s)(1 + T_c s)(1 + T_r s)} U(s) + \frac{K_r}{(1 + T_r s)} D(s) \quad (2.1) \]
\[ y = -a_1 y - a_2 \dot{y} - a_3 y + b_0 u(t - L) \] (2.2)

\[ a_1 = \frac{T_a T_c + T_c T_r + T_r T_a}{T_a T_c T_r} \]
\[ a_2 = \frac{T_a + T_c + T_r}{T_a T_c T_r} \]
\[ a_3 = \frac{1}{T_a T_c T_r} \]
\[ b_0 = \frac{K_a K_c K_r}{T_a T_c T_r} \]

\[ x = [x_1 \ x_2 \ x_3]^T \]
\[ y = [y \ \dot{y}]^T \]

\[ x = Ax + Bu(t - L) \] (2.3)
\[ y = Cx \] (2.4)

\[ A = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
a_3 & a_2 & a_1
\end{bmatrix},
B = \begin{bmatrix}
0 \\
0 \\
b_0
\end{bmatrix},
C = [1 \ 0 \ 0] \]

2.2 (Manoeuvring mode)
¿Í Ç×ÇØ¸ðµå(Navigation mode)¿¡¼­ ÁÖ·Î ¿îÀüµÈ´Ù. ±âµ¿¸ðµå´Â ¼±¹ÚÀÌ ¿¡ Á¢¾È ¶Ç´Â ÃâÇ×Çϰųª ¶Ç´Â Çù¼ö·Î Åë°ú ½Ã ¼±±³ÀÇ Áö·É¿¡ µû¶ó ¼ö½Ã·Î ±× ¼Óµµ¸¦ º¯°æÇÏ´Â ¸ðµåÀ̰í, Ç×ÇØ¸ðµå´Â Ç×±¸¸¦ ¹þ¾î³ª ´ë¾ç ¿¡ ÁøÀÔÇÏ¸é ¾î¶² ÀåÇØ¹°ÀÌ ¹ß°ßµÇÁö ¾Ê´Â ÇÑ ÀÏÁ¤ÇÑ ¼Óµµ·Î(ÀϹÝÀûÀ¸·Î) ¿îÀüÇÏ´Â ¸ðµåÀÌ´Ù.

±âµ¿¸ðµå¿¡¼­´Â ¼±±³¿Í ±â°ü Á¦¾î½Ç°úÀÇ ÅÚ·¡±×·¡ÇÁ ½ÅÈ£¿¡ µû¶ó ¼ö ½Ã·Î ¼Óµµ¸í·ÉÀÌ º¯°æ Çϴ޵ȴÙ. ÀϹÝÀûÀ¸·Î ³× °¡Áö ¼Óµµ¸ðµå Áï, ÃÊ Àú¼Ó(Dead slow speed), Àú¼Ó(Slow speed), Áß¼Ó(Half speed), Àü¼Ó(Full speed)À¸·Î ¿îÀüµÉ ¼ö ÀÖµµ·Ï ¾à¼ÓµÇ¾î ÀÖ°í ½ÇÁ¦ÀÇ ¼Óµµ ¼³Á¤Ä¡´Â ±â°üÀÇ ÇüÅÂ, Ãâ·Â µî¿¡ µû¶ó ¾à°£¾¿ ´Ù¸£´Ù. ¼±±³ÀÇ ¼Óµµ¸í·É¿¡ µû ¶ó ¼³Á¤Ä¡°¡ º¯°æµÇ¸é Á¶¼Ó±â(Governor)´Â ±â°üȸÀü¼ö°¡ ¼³Á¤Ä¡¿¡ °¡±Þ Àû »¡¸® µµ´ÞµÇµµ·Ï Á¶Á¤ÇØÁÙ Çʿ䰡 ÀÖ´Ù.

Ç×ÇØ¸ðµå¿¡¼­ ¼Óµµ Áö·ÉÀº ÀϹÝÀûÀ¸·Î Àü¼Ó¿¡ ¼³Á¤µÈ´Ù. ±â°üÀº Á¶·ù, ¹Ù¶÷, ÆÄµµ µîÀ¸·Î ¼±Ã¼°¡ 6ÀÚÀ¯µµ ¿îµ¿À» ÇÔÀ¸·Î½á ºÎÇÏ ¿Ü¶õÀ» ¹Þ°Ô µÇ°í ÀÌ ¶§¹®¿¡ ¿îÀü Áß ¼Óµµ º¯µ¿ÀÌ ÀϾ°Ô µÈ´Ù. ÀÌ ¶§ Á¶¼Ó±â´Â ¼Óµµ°¡ ¼³Á¤Ä¡¸¦ ¹þ¾î³¯ ¶§ ¸¶´Ù »¡¸® º¹±ÍÇϵµ·Ï Á¶Á¤ÇØÁÙ Çʿ䰡 ÀÖ´Ù.

2.3 ÆÛÁö ¸ðµ¨¸µ

ƯÈ÷ Àú¼Ó, Àú±âÅë ±â°üÀϼö·Ï ¿¬¼Ò°èÅë°ú ȸÀü°èÅëÀÇ ÆÄ¶ó¹ÌÅ͵éÀº ¿îÀü ¼Óµµ¿¡ µû¶ó ¼­ ½ÉÇÏ°Ô º¯µ¿Çϴ Ư¼ºÀ» °¡Áø´Ù.

´ë»ó ½Ã½ºÅÛÀº ¿î ¼Óµµ¿¡ µû¶ó ÆÄ¶ó¹ÌÅ͵éÀÌ º¯µ¿Çϱ⠶§¹®¿¡ Á¦¾ÈµÈ Á¦¾î±âÀÇ ¼º´ÉÀ» È®ÀÎÇϱâ À§Çؼ­´Â Àü¼Óµµ ±¸°£¿¡¼­ ¿¬¼ÓÀûÀ¸·Î º¯µ¿ÇÏ´Â, Áï ½ÇÁ¦ ½Ã ½ºÅÛ°ú À¯»çÇÑ ÅëÆ¯¼ºÀ» °®´Â Á¦¾î´ë»óÀÌ ÇÊ¿äÇÏ´Ù.
Dead slow speed, Slow speed, Half speed, Full speed

\[ F^1(y) = \begin{cases} 
\exp\left(-\frac{(y - m^1)^2}{2(\sigma^1)^2}\right), & y \geq m^1 \\
1, & y < m^1 
\end{cases} \quad (2.5a) \]

\[ F^i(y) = \frac{\exp(- (y - m^i)^2)}{2(\sigma^i)^2}, \quad i = 2, 3 \quad (2.5b) \]

\[ F^4(y) = \begin{cases} 
\exp\left(-\frac{(y - m^4)^2}{2(\sigma^4)^2}\right), & y \leq m^4 \\
1, & y > m^4 
\end{cases} \quad (2.5c) \]
Fig. 2.2 Fuzzy partition of the input space

If y is \( F_1 \), then
\[
x(t) = A_1 x(t) + B_1 u(t - L_1)
\] (2.6a)

If y is \( F_2 \), then
\[
x(t) = A_2 x(t) + B_2 u(t - L_2)
\] (2.6b)

If y is \( F_3 \), then
\[
x(t) = A_3 x(t) + B_3 u(t - L_3)
\] (2.6c)

If y is \( F_4 \), then
\[
x(t) = A_4 x(t) + B_4 u(t - L_4)
\] (2.6d)

\[ \mathcal{H}(t) = \frac{\sum_{i=1}^{4} \rho_i \left[ A^i x(t) + B^i u(t - L^i) \right]}{\sum_{i=1}^{4} \rho_i} \]  

(2.7)

\[ \rho^i = F^i(y) \]  

(2.8)
3.1 PID 제어의 원리

3.1.1 구조의 코드

GA[Gradient] (Gradient) ±âÃÊÇÑ Å½»ö ¾Ë°í¸®Áò°ú´Â ´Þ¸® ·°¬¼Ó¼º, ¹ÌºÐ °¡´É¼º, ´ÜºÀ¼º °°Àº Ž»ö°ø°£¿¡ ´ëÇÑ ºÎ°¡Á¤º¸¸¦ ¿ä±¸ÇÏÁö ¾Ê°í ÇØ ÀÌ¿ëÇÏ¿© ¸Å¿ì Å©°í º¹ÀâÇÑ Å½»ö°ø°£¿¡¼­µµ Àü¿ªÇØ¿¡¼ö·ÅÇÒ ¼ö ÀÖ´Â ÀåÁ¡ ¶§¹®¿¡ ÇÔ¼öÀÇ ÃÖÀûÈ­, ½ÅÈ£ ¹× È­»ó ó¸®, ½Ã½ºÅÛ ½Äº° ¹× Á¦¾î µî ´Ù¾çÇÑ ºÐ¾ß\[11\] ¿¡¼­ ÀÀ¿ëµÇ°í ÀÖ´Ù.

3.1.1.1 구조의 코드

GA[Gradient] ä¿ëµÇ°í ÀÖ´Â ÄÚµù¹ýÀº ÀÌÁøÄÚµù(Binary coding), ½Ç¼öÄÚµù (Real number coding), ±âÈ£ÄÚµù(Symbolic coding)\[11\]µîÀÌ ÀÖ´Ù. ±× Áß ¿¡ ÀÌÁøÄÚµùÀÌ °¡Àå º¸ÆíÀûÀ¸·Î ÀÌ¿ëµÇ°í ÀÖÁö¸¸, Ž»ö¿µ¿ªÀ» È®´ëÇϰÅ³ª, Á¤¹Ðµµ¸¦ ³ôÀÌ°Ô µÇ¸é ¿°»öüÀÇ ±æÀ̰¡ ±æ¾îÁö°Ô µÇ¾î ¿¬»êºÎ´ãÀÌ Áõ°¡ÇÏ´Â ´ÜÁ¡À» °¡Áø´Ù. ÀÌ·¯ÇÑ ´ÜÁ¡À» º¸¿ÏÇϱâ À§ÇØ º» ³í¹®¿¡¼­´Â ¿°»öü(Chromosome)ÀÇ À¯ÀüÀÚ(Gene)¿Í ÇØ º¤ÅÍ ¿ä¼Ò¸¦ ½Ç¼ö·ÎÀÏ´ëÀÏ´ëÀÀ½ÃŲ ½Ç¼öÄÚµùÀ» ä¿ëÇÑ´Ù. ÀÌ·¸°Ô ÇÔÀ¸·Î½á ¿°»öü´Â µ¿Á¶µÉ PID °è¼öÀÇ Á¶ÇÕÀ¸·Î Ç¥½ÃµÈ´Ù.

\[ s= (K_p, T_i, T_d) \]  

(3.1)

\[ K_p, T_i, T_d \] PID ± ¤»¬»»¬ ²­­». ²­­», ²­­»
3.1.2 Genetic operator (Genetic operator)

GA (3.1) is a genetic algorithm that uses three main operators: Reproduction, Crossover, and Mutation. These operators are used to evolve a population of solutions. The Real-coded genetic algorithm (RCGA) is a variation of GA that uses real numbers as the data type.

(1) Reproduction

Reproduction is a process that selects parents from the current population and creates offspring. There are several types of reproduction: Roulette wheel selection-based reproduction, Tournament selection-based reproduction, and Gradient-like reproduction. Jin [5] describes these methods in detail.

xix
(2) 算式

実数型の交叉は、実数型の量を考慮した交叉方法である。以下に、実数型の交叉方法を示す。

<table>
<thead>
<tr>
<th>交叉方法</th>
<th>記述</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat crossover</td>
<td>平面交叉</td>
</tr>
<tr>
<td>Simple crossover</td>
<td>簡単交叉</td>
</tr>
<tr>
<td>Arithmetical crossover</td>
<td>数学者交叉</td>
</tr>
</tbody>
</table>

（11）参照文献.

実数型交叉は、実数型交叉の線形結合（Linear combination）も含まれる。

Fig. 3.1 Modified simple crossover
\[ \tilde{x}_i^1 = \lambda \tilde{x}_i^1 + (1 - \lambda) \tilde{x}_i^2 \quad (3.2a) \]

\[ \tilde{x}_i^2 = \lambda \tilde{x}_i^2 + (1 - \lambda) \tilde{x}_i^1 \quad (1 \leq i \leq n) \quad (3.2b) \]

In general, \( \tilde{x}_1^1, \tilde{x}_1^2 \) and \( \tilde{x}_2^1, \tilde{x}_2^2 \) are ordered to ensure the quality of the GA. \( \tilde{x}_1^1, \tilde{x}_1^2 \) and \( \tilde{x}_2^1, \tilde{x}_2^2 \) are ordered to ensure the quality of the GA. \( \lambda \) is a parameter. \( \tilde{x}_i^1, \tilde{x}_i^2 \) are ordered to ensure the quality of the GA. \( \tilde{x}_i^1, \tilde{x}_i^2 \) are ordered to ensure the quality of the GA.

**3. Local Solution (Dead corner)**

GA (Local solution) and Dead corner (Dead corner) are used to explore the local solutions. Uniform mutation, Boundary mutation, and Dynamic mutation \[^{[11]}\] are used to explore the local solutions. Dynamic mutation.
\[ x_j = \begin{cases} 
\tilde{x}_j + \Delta(k, x_j^{(U)} - \tilde{x}_j), & \text{if } \tau = 0 \\
\tilde{x}_j - \Delta(k, \tilde{x}_j - x_j^{(L)}), & \text{if } \tau = 1 
\end{cases} \] (3.3)

\[ \Delta(k, y) = y \cdot r \cdot (1 - \frac{k}{T}) \] (3.4)

3.1.3...
3.1.4  

Elitist strategy

3.1.4.1  

Elitist strategy (Fitness)
3.2 RCGA ±â¹ÝÀÇ PID Á¦¾î±â ¼³°è

Á¿Àê¿ì Á¿³ç (Governor)²º ÀÔÀ½¿¡µµ ÇöÀå ±â¼úÀÚ¿¡°Ô Ä£¼÷Çϰí, ´Ü ¼øÇϸ鼭µµ ºÒÈ®½Ç¼º¿¡ °­ÀÎÇÑ PID Á¦¾î ¾Ë°í¸®ÁòÀ¸·Î ±¸ÇöµÇ°í ÀÖ. ¾Õ¼­ ¹àÇûµíÀÌ ±â°ü ½Ã½ºÅÛÀº ¿îÀüÁ¶°ÇÀÌ ¹Ù²î¸é Á¶¼Ó±âÀÇ ¼º´É ÀÌ ¶³¾îÁö¸ç, ÃÖÀûÀÇ ¼º´ÉÀ» ¾ò±â À§Çؼ­´Â »ç¿ëÀÚ°¡ Á¦¾î±âÀÇ ¸Å°³º¯¼öµéÀ» ÀûÀýÈ÷ Á¶ÀýÇØ ÁÖ¾î¾ß ÇÑ´Ù. ½ÇÁ¦·Î ¼±¹Ú±â°üÀº ´ëºÎºÐ Ç×ÇØ¸ðµå¿¡¼­ ¿îÀüµÇ±â ¶§¹®¿¡ ÀÌ ¿îÀü¸ðµå¿¡¸Âµµ·Ï Á¦¾î±âÀÇ °è¼ö°¡¼³Á¤µÇ¸é Àú¼Ó¿îÀü¿¡¼­ ½Ã°£Áö¿¬ÀÌ Ä¿Á® Áö±Û¸µ Çö»óÀÌ ÀϾ´Â ¹®Á¦Á¡µéÀÌ ÁöÀûµÇ°í ÀÖ´Ù. Á¦¾î±â ¼³°è¸¦ À§ÇØ ¸¹ÀÌ »ç¿ë µÇ¾îÁö°í ÀÖ´Â ½ÃÇàÂø¿À¹ýÀ̳ª ÀÀ´ä°î¼± ¹æ¹ýµéÀº Áö³ªÄ¡°Ô ¹ø°Å·Î¿î °á°ú·Î¾ò¾îÁö°í, Á¦¾î±âÀÇ ¼º´É ¶ÇÇÑ ¿ì¼öÇÏÁö ¾Ê´Ù. ¶ÇÇÑ ±âÁ¸ÀÇ ¹æ¹ýµé ÀÇ °øÁ¤ È®ÀÎÀ» Çϴµ¥ ÀÖ¾î Á¦ÇÑµÈ Á¤º¸¸¸À» À̲ø¾î³»±â ¶§¹®¿¡ ¼³°èµÈ PID Á¦¾î±âÀÇ ¼º´ÉÀº ±ØÈ÷ Á¦ÇÑÀûÀÌ¸ç ¶ÇÇÑ ¿Â¶óÀÎ ¿îÀü¿¡´ÂºÎÀûÇÕÇÑ º¹À⼺°ú ¼öÄ¡ÀûÀÎ ³­Á¡µéÀ» °¡Áö°í ÀÖ´Ù. ±×·¡¼­ ÀÌ·± ±âÁ¸ ¹æ¹ýµéÀÇ ´ÜÁ¡À» ±Ùº»ÀûÀ¸·Î ±Øº¹ÇÒ ¼ö ÀÖ´Â »õ·Î¿î ¿Â¶óÀÎ °øÁ¤È®ÀÎ ¹æ¹ýÀÌ ¿ä±¸µÈ´Ù.

°¢ ¿îÀü¸ðµå¿¡¼­ PID Á¦¾î±âÀÇ ÆÄ¶ó¹ÌÅÍ °áÁ¤Àº Ziegler-Nichols µ¿Á¶¹ý, ±Ø-¿µÁ¢ ¹èÄ¡¹ý, IMC-PID µ¿Á¶¹ý µî ¿©·¯ ¹æ¹ýÀ¸·Î µ¿Á¶ÇÏ´Â °Í
\[ J = \int_0^{t_r} |e(t)| \, dt \]  \hspace{1cm} (3.5)

Fig. 3.2 Parameter tuning of the PID controller using a RCGA
(3.6)\[ f(s(k)) = -F(x(k)) - r \]

\[ f(s(k)) \geq 0, \quad F(x(k)) \geq 0 \quad \text{for all } k, \quad r \geq 0 \]

3.3 \( \text{Gain scheduling} \)
Local controller, Interpolation, Overall controller, Scheduling variable.

If-then rules of Takagi-Sugeno type.
If $y(t)$ is $F^1$, then $u^1(t)=K_p^1 e(t) + K_v^1 \int e(t) dt + K_{d1}^1 \frac{de(t)}{dt}$ \hspace{1cm} (3.7a)

If $y(t)$ is $F^2$, then $u^2(t)=K_p^2 e(t) + K_v^2 \int e(t) dt + K_{d2}^2 \frac{de(t)}{dt}$ \hspace{1cm} (3.7b)

If $y(t)$ is $F^3$, then $u^3(t)=K_p^3 e(t) + K_v^3 \int e(t) dt + K_{d3}^3 \frac{de(t)}{dt}$ \hspace{1cm} (3.7c)

If $y(t)$ is $F^4$, then $u^4(t)=K_p^4 e(t) + K_v^4 \int e(t) dt + K_{d4}^4 \frac{de(t)}{dt}$ \hspace{1cm} (3.7d)

If $y(t)$ is $F^1, F^2, F^3, F^4$, then $u(t)$ is a PID controller, $K_p^i, K_v^i, K_{d}^i$ are the PID parameters.

If $y(t)$ is $F^1, F^2, F^3, F^4$, $u(t)$ is a PID controller, $K_p^i, K_v^i, K_{d}^i$ are the PID parameters.

(3.8)

\[ u(t) = \sum_{i=1}^{4} \rho^i u^i(t) \hspace{1cm} \sum_{i=1}^{4} \rho^i \] \hspace{1cm} (3.8)

\[ \rho^i = F^i(y) \hspace{1cm} (3.9) \]
Fig. 3.3 Schematic diagram of the fuzzy PID Controller
## 4.1 4L80MC

**B&W** 4L80MC µðÁ©±â°üÀº Àú¼Ó, ÀåÇàÁ¤ ±â°üÀ̶⃧§¹®¿¡ žÀçµÉ ¼± ¹Ú¿¡ µû¶ó ¾à°£ÀÇ Â÷ÀÌ´Â ÀÖ°ÚÁö¸¸ µ¿ÀÛÁ¡À» ÆÄ¶ó(20rpm), ÀÌ ¶§ ÃßÁ¤µÈ ÆÄ¶ó ¹ÌÅÍÀÇ ±Ù»ç°ªÀº Ç¥ 4.1[18]°ú °°´Ù. À̶§ Æ÷È­ ÀԷ°ª α⃧ 10⃧⃧ 10⃧⃧ .

### 4.1 4L80MC  Diesel engine parameters at 4 operating points

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model</th>
<th>Dead slow</th>
<th>Slow</th>
<th>Half</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [sec]</td>
<td></td>
<td>1.50</td>
<td>0.75</td>
<td>0.50</td>
<td>0.38</td>
</tr>
<tr>
<td>Tₐ [sec]</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Kᵦ [BHP/mm]</td>
<td></td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Tₜ [sec]</td>
<td></td>
<td>0.075</td>
<td>0.037</td>
<td>0.025</td>
<td>0.019</td>
</tr>
<tr>
<td>Kₜ [BHP/mm]</td>
<td></td>
<td>16.345</td>
<td>42.16</td>
<td>81.87</td>
<td>122.47</td>
</tr>
<tr>
<td>Tᵦ [sec]</td>
<td></td>
<td>3.65</td>
<td>3.308</td>
<td>2.382</td>
<td>1.787</td>
</tr>
<tr>
<td>Kᵦ [rpm/ BHP]</td>
<td></td>
<td>0.045</td>
<td>0.020</td>
<td>0.010</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Ziegler-Nichols  IMC  PID  D
4.2 Model reduction using a RCGA

Table 4.2 Model reduction using a RCGA

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Dead slow</th>
<th>Slow</th>
<th>Half</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ</td>
<td>3.648</td>
<td>3.307</td>
<td>2.386</td>
<td>1.788</td>
</tr>
<tr>
<td>L</td>
<td>1.68</td>
<td>0.89</td>
<td>0.624</td>
<td>0.51</td>
</tr>
</tbody>
</table>

4.2 ifestyles

4.1 ifestyles
\[ u_i(t) = u_{0i} + 0.4 \sin(0.7 \omega_i t) + 0.3 \sin(\omega_i t) + 0.2 \sin(1.7 \omega_i t) \quad (4.1) \]

\[ i = 1, 2, 3, 4 \]

\( u_0 \) is the cut-off frequency. 

\( 4.1 \) represents the equation (4.1) as a fuzzy model. 

A plot showing the speed in rpm over time is included, demonstrating the fuzzy model and the dead-slow model.
Fig. 4.1 Responses of the fuzzy model and the dead-slow speed model

Fig. 4.2 Responses of the fuzzy model and the slow speed model
4.3 Responses of the fuzzy model and the half speed model

Fig. 4.3 Responses of the fuzzy model and the half speed model
Fig. 4.4 Responses of the fuzzy model and the full speed model

4.3 PID

4.4
### Table 4.3 Tuned PID parameters and performances

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dead slow</th>
<th>Slow</th>
<th>Half</th>
<th>Full</th>
</tr>
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**Fig. 4.5 Step response of the RCGA-tuned PID control system for the dead-slow speed model**
Fig. 4.6 Step response of the RCGA-tuned PID control system for the slow speed model.

Fig. 4.7 Step response of the RCGA-tuned PID control system for the half speed model.
Fig. 4.8 Step response of the RCGA-tuned PID control system for the full speed model.

4.9

xxxviii
Fig. 4.9 Step response of the proposed control system
Fig. 4.10 Step response of the Z-N tuned PID control system for the dead-slow speed model.
Fig. 4.11 Step response of the Z-N tuned PID control system for the full speed model
Fig. 4.12 Step response of the IMC tuned PID control system for the dead slow speed model.

Fig. 4.13 IMC vs PID control system.
Fig. 4.13 Step response of the IMC tuned PID control system for the full speed model

4.5
Fig 4.14 Response of the Fuzzy PID control system to a step-type disturbance change
Fig. 4.15 Response of the Z-N PID control system to a step-type disturbance change

Fig. 4.16 Response of the IMC PID control system to a step-type disturbance change
5

PID

RCC

PID

RCGA


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