Advanced Control Library

User Reference Manual

56800E
Digital Signal Controller
The following revision history table summarizes changes contained in this document.

Table 0-1. Revision History

<table>
<thead>
<tr>
<th>Date</th>
<th>Revision Label</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Initial release</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Reformatted and updated revision</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>FSLESL 2.0</td>
</tr>
</tbody>
</table>
Chapter 1  License Agreement

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Chapter 2 INTRODUCTION

2.1 Overview

This Reference Manual describes Advanced Control Library for Freescale 56F800E family of Digital Signal Controllers. This library contains optimized functions for 56F800E family of controllers. The library is supplied in a binary form, which is unique by its simplicity to integrate with user application. For correct functionality of Motor Control Library, General Functions Library (GFLIB) must be installed and included in the application project.

2.2 Supported Compilers

Advanced Control Library (ACLIB) is written in assembly language with C-callable interface. The library was built and tested using following compiler:

1. CodeWarrior™ Development Studio for Freescale™ DSC56800/E Digital Signal Controllers, version 8.3

The library is delivered in library module 56F800E_ACLIB.lib and is intended for use in small data memory model projects. The interfaces to the algorithms included in this library have been combined into a single public interface include file, aclib.h. This was done to simplify the number of files required for inclusion by application programs. Refer to the specific algorithm sections of this document for details on the software Application Programming Interface (API), defined and functionality provided for the individual algorithms.

2.3 Installation

If the user wants to fully use this library, the CodeWarrior tools should be installed prior to the Advanced Control Library. In case that Advanced Control Library tool is installed while CodeWarrior is not present, users can only browse the installed software package, but will not be able to build, download, and run the code. The installation itself consists of copying the required files to the destination hard drive, checking the presence of CodeWarrior, and creating the shortcut under the Start->Programs menu.

Each Advanced Control Library release is installed in its own new folder named 56800E_ACLIB_rX.X, where X.X denotes the actual release number. This way of library installation allows users to maintain older releases and projects and gives them a free choice to select the active library release.
To start the installation process, follow the following steps:

1. Execute 56800E_FSLESL_RXX.exe
2. Follow the Advanced Control Library software installation instructions on your screen.

2.4 Library integration

The Advanced Control Library is added into a new CodeWarrior project by taking the following steps:

1. Create a new empty project.
2. Create ACLIB group in your new open project. Note that this step is not mandatory, it is mentioned here just for the purpose of maintaining file consistency in the CodeWarrior project window. In the CodeWarrior menu, choose Project > Create Group..., type ACLIB into the dialog window that pops up, and click <OK>.
3. Refer the 56800E_ACLIB.lib file in the project window. This can be achieved by dragging the library file from the proper library subfolder and dropping it into the ACLIB group in the CodeWarrior project window. This step will automatically add the ACLIB path into the project access paths, such as the user can take advantage of the library functions to achieve flawless project compilation and linking.
4. It is similar with the reference file aclib.h. This file can be dragged from the proper library subfolder and dropped into the ACLIB group in the CodeWarrior project window.
5. The following program line must be added into the user-application source code in order to use the library functions.
   
   #include "aclib.h"

6. Since Advanced Control Library is not stand-alone, General Functions Library (GFLIB) and Motor Control Library (MCLIB) must be installed and included in the application project prior to ACLIB.
7. Create GFLIB group in your new open project. Note that this step is not mandatory, it is mentioned here just for the purpose of maintaining file consistency in the CodeWarrior project window. In the CodeWarrior menu, choose Project > Create Group..., type GFLIB into the dialog window that pops up, and click <OK>.
8. Refer the 56800E_GFLIB.lib file in the project window. This can be done by dragging the library file from the proper library subfolder and dropping it into the GFLIB group in the CodeWarrior project window. This step will automatically add the GFLIB path into the project access paths, such as the user can take advantage of the library functions to achieve flawless project compilation and linking.
9. It is similar with the reference file `gflib.h` in the project window. This can be achieved by dragging the file from the proper library subfolder and dropping it into the `GFLIB` group in the CodeWarrior project window.

10. Create `MCLIB` group in your new open project. Note that this step is not mandatory, it is mentioned here just for the purpose of maintaining file consistency in the CodeWarrior project window. In the CodeWarrior menu, choose Project > Create Group..., type MCLIB into the dialog window that pops up, and click <OK>.

11. Refer the `56800E_ACLIB.lib` file in the project window. This can be done by dragging the library file from the proper library subfolder and dropping it into the `MCLIB` group in the CodeWarrior project window. This step will automatically add the `MCLIB` path into the project access paths, such as the user can take the advantage of the library functions to achieve flawless project compilation and linking.

12. It is similar with the reference file `mclib.h` in the project window. This can be achieved by dragging the file from proper library subfolder and dropping it into the `MCLIB` group in the CodeWarrior project window.

13. The following program lines must be added into the user application source code in order to use the library functions.

```
#include "gflib.h"
#include "mclib.h"
```

### 2.5 API definition

The description of each function described in this Advanced Control Library user reference manual consists of a number of subsections:

**Synopsis**

This subsection gives the header files that should be included within a source file that references the function or macro. It also shows an appropriate declaration for the function or for a function that can be substituted by a macro. This declaration is not included in your program; only the header file(s) should be included.

**Prototype**

This subsection shows the original function prototype declaration with all its arguments.

**Arguments**

This optional subsection describes input arguments to a function or macro.

**Description**

This subsection is a description of the function or macro. It explains algorithms being used by functions or macros.
2.6 Data Types

The 16-bit DSC core supports four types of two’s-complement data formats:

- Signed integer
- Unsigned integer
- Signed fractional
- Unsigned fractional

The Signed and unsigned integer data types are useful for general-purpose computation; they are familiar with the microprocessor and microcontroller programmers. Fractional data types allow powerful numeric and digital-signal-processing algorithms to be implemented.

2.6.1 Signed Integer (SI)

This format is used for processing data as integers. In this format, the N-bit operand is represented using the N.0 format (N integer bits). The signed integer numbers lie in the following range:
This data format is available for bytes, words, and longs. The most negative, signed word that can be represented is \(-32,768\) ($\text{8000}$), and the most negative, signed long word is \(-2,147,483,648\) ($\text{80000000}$).

The most positive, signed word is 32,767 ($\text{7FFF}$), and the most positive signed long word is 2,147,483,647 ($\text{7FFFFFFF}$).

### 2.6.2 Unsigned Integer (UI)

The unsigned integer numbers are positive only, and they have nearly twice the magnitude of a signed number of the same size. The unsigned integer numbers lie in the following range:

\[-2^{(N-1)} \leq SI \leq 2^{(N-1)} - 1\] \hspace{1cm} Eqn. 2-1

The binary word is interpreted as having a binary point immediately to the right of the integer’s least significant bit. This data format is available for bytes, words, and long words. The most positive, 16-bit, unsigned integer is 65,535 ($\text{FFFF}$), and the most positive, 32-bit, unsigned integer is 4,294,967,295 ($\text{FFFFFFFF}$). The smallest unsigned integer number is zero ($\text{0000}$), regardless of size.

### 2.6.3 Signed Fractional (SF)

In this format, the N-bit operand is represented using the $1.[N-1]$ format (one sign bit, $N-1$ fractional bits). The signed fractional numbers lie in the following range:

\[0 \leq SF \leq 1.0 - 2^{-(N-1)}\] \hspace{1cm} Eqn. 2-3

This data format is available for words and long words. For both word and long-word signed fractions, the most negative number that can be represented is \(-1.0\); its internal representation is $\text{8000}$ (word) or $\text{80000000}$ (long word). The most positive word is $\text{7FFF}$ ($1.0 - 2^{-15}$); its most positive long word is $\text{7FFFFFFF}$ ($1.0 - 2^{-31}$).

### 2.6.4 Unsigned Fractional (UF)

The unsigned fractional numbers can be positive only, and they have nearly twice the magnitude of a signed number with the same number of bits. The unsigned fractional numbers lie in the following range:

\[0,0 \leq UF \leq 2.0 - 2^{-(N-1)}\] \hspace{1cm} Eqn. 2-4

The binary word is interpreted as having a binary point after the MSB. This data format is available for words and longs. The most positive, 16-bit, unsigned
number is $FFFF$, or $\{1.0 + (1.0 - 2^{-[N-1]})\} = 1.99997$. The smallest unsigned fractional number is zero ($0000$).

2.7 User Common Types

<table>
<thead>
<tr>
<th>Mnemonics</th>
<th>Size — bits</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Word8</td>
<td>8</td>
<td>To represent 8-bit signed variable/value.</td>
</tr>
<tr>
<td>UWord8</td>
<td>8</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Word16</td>
<td>16</td>
<td>To represent 16-bit signed variable/value.</td>
</tr>
<tr>
<td>UWord16</td>
<td>16</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Word32</td>
<td>32</td>
<td>To represent 32-bit signed variable/value.</td>
</tr>
<tr>
<td>UWord32</td>
<td>32</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Int8</td>
<td>8</td>
<td>To represent 8-bit signed variable/value.</td>
</tr>
<tr>
<td>UInt8</td>
<td>8</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Int16</td>
<td>16</td>
<td>To represent 16-bit signed variable/value.</td>
</tr>
<tr>
<td>UInt16</td>
<td>16</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Int32</td>
<td>32</td>
<td>To represent 32-bit signed variable/value.</td>
</tr>
<tr>
<td>UInt32</td>
<td>32</td>
<td>To represent 16-bit unsigned variable/value.</td>
</tr>
<tr>
<td>Frac16</td>
<td>16</td>
<td>To represent 16-bit signed variable/value.</td>
</tr>
<tr>
<td>Frac32</td>
<td>32</td>
<td>To represent 32-bit signed variable/value.</td>
</tr>
<tr>
<td>NULL</td>
<td>constant</td>
<td>Represents NULL pointer.</td>
</tr>
<tr>
<td>bool</td>
<td>16</td>
<td>Boolean variable.</td>
</tr>
<tr>
<td>false</td>
<td>constant</td>
<td>Represents false value.</td>
</tr>
<tr>
<td>true</td>
<td>constant</td>
<td>Represents true value.</td>
</tr>
<tr>
<td>FRAC16()</td>
<td>macro</td>
<td>Transforms float value from $&lt;-1, 1)$ range into fractional representation $&lt;-32768, 32767&gt;$.</td>
</tr>
<tr>
<td>FRAC32()</td>
<td>macro</td>
<td>Transforms float value from $&lt;-1, 1)$ range into fractional representation $&lt;-2147483648, 2147483648&gt;$.</td>
</tr>
</tbody>
</table>
2.8 Special Issues

All functions in Advanced Control Library are implemented without storing any of the volatile register used by the respective routine. Only non-volatile registers (for list of volatile/non-volatile registers refer to the compiler manual) are saved by pushing the registers on the stack. Therefore if the particular registers initialized before the library function call are to be used after the function call, it is necessary to save them manually.

### Table 2-2. User-Defined Typedefs in mclib_types.h

<table>
<thead>
<tr>
<th>Name</th>
<th>Structure Members</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCLIB_3_COOR_SYST_T</td>
<td>Frac16 f16A</td>
<td>three phase system</td>
</tr>
<tr>
<td></td>
<td>Frac16 f16B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frac16 f16C</td>
<td></td>
</tr>
<tr>
<td>MCLIB_2_COOR_SYST_T</td>
<td>Frac16 f16A</td>
<td>two phase system</td>
</tr>
<tr>
<td></td>
<td>Frac16 f16B</td>
<td></td>
</tr>
<tr>
<td>MCLIB_2_COOR_SYST_ALPHA_BETA_T</td>
<td>Frac16 f16Alpha</td>
<td>two phase system — alpha/beta</td>
</tr>
<tr>
<td></td>
<td>Frac16 f16Beta</td>
<td></td>
</tr>
<tr>
<td>MCLIB_2_COOR_SYST_D_Q_T</td>
<td>Frac16 f16D</td>
<td>two phase system — generic DQ</td>
</tr>
<tr>
<td></td>
<td>Frac16 f16Q</td>
<td></td>
</tr>
<tr>
<td>MCLIB_ANGLE_T</td>
<td>Frac16 f16Sin</td>
<td>two phase system — sine and cosine components</td>
</tr>
<tr>
<td></td>
<td>Frac16 f16Cos</td>
<td></td>
</tr>
</tbody>
</table>
## Chapter 3  FUNCTION API

### 3.1  API Summary

Table 3-1. API functions summary

<table>
<thead>
<tr>
<th>Name</th>
<th>Arguments</th>
<th>Output</th>
<th>Description</th>
</tr>
</thead>
</table>
| ACLIB_PMSMBemfObservAB    | MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtIalbet  
MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtIalbet  
Frac16 f16Speed  
ACLIB_BEMF_OBSRV_AB_T * const pudtCtrl | void   | This function calculates the algorithms of finding permanent-magnet axis.                                         |
| ACLIB_PMSMBemfObserv12AB  | MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtIalbet  
MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtIalbet  
Frac16 f16Speed  
ACLIB_BEMF_OBSRV_AB_T * const pudtCtrl | void   | This function calculates the algorithms of finding permanent-magnet axis. This version uses the quicker 12-bit precision sine calculation therefore it is quicker but with reduced precision in comparison to ACLIB_PMSMBemfObservAB. |
| ACLIB_AngleTrackObserv    | MCLIB_ANGLE_T *pudtSinCos  
ACLIB_ANGLE_TRACK_OBSRV_T * const pudtCtrl | void   | This function calculates the algorithm of velocity and position-tracking observer.                               |
| ACLIB_AngleTrackObserv12  | MCLIB_ANGLE_T *pudtSinCos  
ACLIB_ANGLE_TRACK_OBSRV_T * const pudtCtrl | void   | This function calculates the algorithm of velocity and position-tracking observer. This version uses the quicker 12-bit precision sine calculation therefore it is quicker but with reduced precision in comparison to ACLIB_AngleTrackObserv. |
| ACLIB_TrackObserv         | Frac16 f16ThetaErr  
ACLIB_TRACK_OBSRV_T * const pudtCtrl | void   | This function calculates the tracking observer for determination angular speed and position of input error functional signal. |
| ACLIB_PMSMBemfObservDQ    | MCLIB_2_COOR_SYST_D_Q_T *pudtIdq  
MCLIB_2_COOR_SYST_D_Q_T *pudtIdq  
Frac16 f16Speed  
ACLIB_BEMF_OBSRV_DQ_T * const pudtCtrl | void   | The function calculates the algorithm of back electro-motive force observer in rotating reference frame.         |
| ACLIB_Integrator          | Frac16 f16X  
ACLIB_INTEGRATOR_T * pudtIntg | void   | The function calculates the algorithm of numerical integrator of its input.                                       |
3.2  ACLIB_PMSMBemfObsrvAB

The function calculates the algorithm of back electro-motive force observer in stationary reference frame.

3.2.1  Synopsis

```c
#include "aclib.h"
void ACLIB_PMSMBemfObsrvAB(
   MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtCurrentAlphaBeta,
   MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtVoltageAlphaBeta,
   Frac16 f16Speed,
   ACLIB_BEMF_OBSRV_AB_T *pudtCtrl)
```

3.2.2  Prototype

```c
asm void ACLIB_PMSMBemfObsrvABFAsm(MCLIB_2_COOR_SYST_ALPHA_BETA_T
   *pudtCurrentAlphaBeta, MCLIB_2_COOR_SYST_ALPHA_BETA_T
   *pudtVoltageAlphaBeta, Frac16 f16Speed, ACLIB_BEMF_OBSRV_AB_T *pudtCtrl)
```

3.2.3  Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*pudtCurrentAlphaBeta</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_ALPHA_BETA_T</td>
<td>N/A</td>
<td>Input signal of alpha/beta current components.</td>
</tr>
<tr>
<td>*pudtVoltageAlphaBeta</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_ALPHA_BETA_T</td>
<td>N/A</td>
<td>Input signal of alpha/beta voltage components.</td>
</tr>
<tr>
<td>f16Speed</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Fraction value of electrical speed.</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_BEMF_OBSRV_AB_T</td>
<td>N/A</td>
<td>Pointer to an observer structure, which contains coefficients.</td>
</tr>
</tbody>
</table>
### 3.2.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for 56800E platforms.

---

### Table 3-3. User Types

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>udtEObsrv.f32Alpha</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in beta axis.</td>
</tr>
<tr>
<td>udtEObsrv.f32Beta</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in beta axis.</td>
</tr>
<tr>
<td>udtIObsrv.f32Alpha</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated current in alpha axis.</td>
</tr>
<tr>
<td>udtIObsrv.f32Beta</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated current in beta axis.</td>
</tr>
<tr>
<td>udtCtrl.f32lAlpha_1</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>State variable in alpha part of the observer; integral part at step k-1.</td>
</tr>
<tr>
<td>udtCtrl.f32lBeta_1</td>
<td>sf32</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>State variable in beta part of the observer; integral part at step k-1.</td>
</tr>
<tr>
<td>udtCtrl.f16PropScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer proportional gain.</td>
</tr>
<tr>
<td>udtCtrl.i16PropShift</td>
<td>si16</td>
<td>SI16</td>
<td>-F...F</td>
<td>Observer proportional gain shift.</td>
</tr>
<tr>
<td>udtCtrl.f16IntegScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer integral gain.</td>
</tr>
<tr>
<td>udtCtrl.i16IntegShift</td>
<td>si16</td>
<td>SI16</td>
<td>-F...F</td>
<td>Observer integral gain shift.</td>
</tr>
<tr>
<td>mcUnityVctr.f16Sin</td>
<td>mclib_angle_t</td>
<td></td>
<td>$8000...$7FFF</td>
<td>Sine component of estimated unity vector.</td>
</tr>
<tr>
<td>mcUnityVctr.f16Cos</td>
<td>mclib_angle_t</td>
<td></td>
<td>$8000...$7FFF</td>
<td>Cosine component of estimated unity vector.</td>
</tr>
<tr>
<td>f16IScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for current $I_{FRAC}$.</td>
</tr>
<tr>
<td>f16UScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for voltage $U_{FRAC}$.</td>
</tr>
<tr>
<td>f16WIScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for angular speed $W_{FRAC}$.</td>
</tr>
<tr>
<td>f16EScaled</td>
<td>sf16</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for back-EMF $E_{FRAC}$.</td>
</tr>
</tbody>
</table>
3.2.5 Dependencies

List of all dependent files:
- 56800E_types.h
- 56800E_MCLIB library
- 56800E_GFLIB library
- ACLIB_AngleTrackObsrvAsm.h
- aclib.h

3.2.6 Description

This back-emf observer is realized within stationary $\alpha, \beta$ reference frame.

$$
\begin{bmatrix}
    u_{\alpha} \\
    u_{\beta}
\end{bmatrix} = R_s \begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} + \begin{bmatrix}
    s L_D & \Delta L \omega_r \\
    -\Delta L \omega_r & s L_D
\end{bmatrix} \begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} + (\Delta L \cdot (\omega_r i_D - i_{\beta}) + k_e \omega_r) \cdot \begin{bmatrix}
    -\sin(\theta_r) \\
    \cos(\theta_r)
\end{bmatrix}
$$

Eqn. 3-1

where
- $R_s$ stator resistance
- $L_d, L_q$ - D-axis and Q-axis inductance
- $k_e$ back-EMF constant
- $\omega_r$ rotor angular speed
- $u_{\alpha}, u_{\beta}$ components of stator voltage vector
- $i_{\alpha}, i_{\beta}$ components of stator current vector
- $s$ operator of derivative
- $i_{\beta}^*$ first derivative of $i_{\beta}$ current
- $\Delta L = (L_d - L_q)$ motor saliency

This extended back-EMF model includes both position information from the conventionally defined back-EMF and the stator inductance as well. This allows to extracts the rotor position and velocity information by estimating the extended back EMF only.

Both alpha and beta-axis consists of the stator current observer based on RL motor circuit which requires motor parameters.

The current observer is fed by the sum of the actual applied motor voltage, cross-coupled rotational term, which corresponds to the motor saliency $(L_d - L_q)$ and compensator corrective output. The observer provides back-EMF signals as disturbance because back-EMF is not included in observer model.
Figure 3-1. Block diagram of back-emf observer

It is obvious that the accuracy of the back EMF estimates is determined by the correctness of used motor parameters (R, L) by fidelity of the reference stator voltage and by quality of compensator such as bandwidth, phase lag and so on.

Appropriate dynamic behavior of the back emf observer is achieved by placement of the poles of the stator current observer characteristic polynomial. This general method is based on matching the coefficients of the characteristic polynomial with the coefficients of the general second-order system.

$$\ddot{E}_{\alpha\beta}(s) = -E_{\alpha\beta}(s) \cdot \left[ \frac{F_c(s)}{sL_D + R_S + F_c(s)} \right]$$  

Eqn. 3-2

Back emf observer is Luenberger type observer with motor model which is realized in fixed point arithmetic transformed using backward Euler transformation.

$$i_{FRFAC}(k) = U_{FRAC} \cdot u_{FRAC}(k) + E_{FRAC} \cdot e_{FRAC}(k) - W_{FRAC} \cdot \omega_{FRAC} \cdot i'_{FRAC}(k) - I_{FRAC} \cdot i_{FRAC}(k-1)$$  

Eqn. 3-3

where

- $i_{FRFAC}(k) = [i_\alpha, i_\beta]$ is fractional representation of stator current vector
- $u_{FRAC}(k) = [u_\alpha, u_\beta]$ is fractional representation of stator voltage vector
- $e_{FRAC}(k) = [e_\alpha, e_\beta]$ is fractional representation of stator back-emf voltage vector
- $i'_{FRAC}(k) = [i_\beta, -i_\alpha]$ is fractional representation of complementary stator current vector
- $\omega_{FRAC}(k)$ is fractional representation of angular speed

Scaling coefficients relating to maximal values are expressed as

$$U_{FRAC} = \frac{\Delta T_S}{L_d + \Delta T_S R_S} \cdot \frac{U_{MAX}}{I_{MAX}}$$  

Eqn. 3-4
where
- $\Delta T_s$ sampling time in [sec]
- $I_{MAX}$ maximal peak current in [A]
- $E_{MAX}$ maximal peak back-emf voltage in [V]
- $U_{MAX}$ maximal peak stator voltage in [V]
- $\Omega_{MAX}$ maximal angular speed in [rad/sec]

If a Luenberger type stator current observer is properly designed in the stationary reference frame, the back-EMF can be estimated as a disturbance, produced by the observer controller. This is only valid however if the back-EMF term is not included in the observer model. The observer is actually a closed loop current observer so it acts as a state filter for the back-EMF term.

The estimate of extended EMF term can be derived from Equation 3-2 as follows:

$$\frac{\hat{E}_{\alpha\beta}(s)}{E_{\alpha\beta}(s)} = \frac{sK_p + K_i}{s^2 L_D + sR_s + sK_p + K_i}$$

Eqn. 3-8

The observer controller can be designed by comparing the closed loop characteristic polynomial with that of a standard second order system as:

$$s^2 + \frac{K_p + R_s}{L_D} \cdot s + \frac{K_i}{L_D} = s^2 + 2\xi\omega_0 s + \omega_0^2$$

Eqn. 3-9

where
- $\omega_0$ is the natural frequency of the closed loop system (loop bandwidth)
- $\xi$ is the loop attenuation.

### 3.2.7 Returns

The function returns a unity vector representing the estimated value of sine and cosine values of back emf.
### 3.2.8 Implementation

#### Example 3-1. Implementation Code

```c
#include "gflib.h"
#include "mclib.h"
#include "aclib.h"

MCLIB_2_COOR_SYST_ALPHA_BETA_T mcI, mcU;
ACLIB_BEMF_OBSRV_AB_T acBemfObsrv;

void Isr(void);

void main (void)
{
    acBemfObsrv.udtEObsrv.f32Alpha = FRAC32(0.0);
    acBemfObsrv.udtEObsrv.f32Beta = FRAC32(0.0);
    acBemfObsrv.udtIObsrv.f32Alpha = FRAC32(0.0);
    acBemfObsrv.udtIObsrv.f32Beta = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f32IAlpha_1 = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f32IBeta_1 = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f16F16PropScaled = BEMFOBSRV_AB_PROP_GAIN_SCALED;
    acBemfObsrv.udtCtrl.f16PropShift = BEMFOBSRV_AB_PROP_GAIN_SHIFT;
    acBemfObsrv.udtCtrl.f16IntegScaled = BEMFOBSRV_AB_INTEG_GAIN_SCALED;
    acBemfObsrv.udtCtrl.f16IntegShift = BEMFOBSRV_AB_INTEG_GAIN_SHIFT;
    acBemfObsrv.f16IScaled = BEMFOBSRV_AB_I_SCALED;
    acBemfObsrv.f16UScaled = BEMFOBSRV_AB_U_SCALED;
    acBemfObsrv.f16EScaled = BEMFOBSRV_AB_E_SCALED;
    acBemfObsrv.f16WIScaled = BEMFOBSRV_AB_WI_SCALED;
}

/* Periodical function or interrupt */
void ISR(void)
{
    ACLIB_PMSMBemfObsrvAB(&mcI,&mcU,f16Speed,&acBemfObsrv);
}
```

### 3.2.9 Performance

#### Table 3-4. Performance of ACLIB_PMSMBemfObsrvAB function

<table>
<thead>
<tr>
<th>Code Size (words)</th>
<th>168 + 65 (GFLIB_SqrtPoly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Size (words)</td>
<td>0 + 34 (GFLIB_SqrtPoly)</td>
</tr>
<tr>
<td>Execution Clock</td>
<td>Min 257/238 cycles</td>
</tr>
<tr>
<td></td>
<td>Max 325/301 cycles</td>
</tr>
</tbody>
</table>
3.3 ACLIB_PMSMBemfObsrv12AB

The function calculates the algorithm of back electro-motive force observer in stationary reference frame. This version uses the quicker 12-bit precision sine calculation therefore it is quicker but with reduced precision in comparison to ACLIB_PMSMBemfObsrvAB.

3.3.1 Synopsis

#include "aclib.h"
void ACLIB_PMSMBemfObsrv12AB(  
MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtCurrentAlphaBeta,  
MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtVoltageAlphaBeta,  
Frac16 f16Speed,  
ACLIB_BEMF_OBSRV_AB_T *pudtCtrl)

3.3.2 Prototype

asm void ACLIB_PMSMBemfObsrv12ABFAsm(MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtCurrentAlphaBeta, MCLIB_2_COOR_SYST_ALPHA_BETA_T *pudtVoltageAlphaBeta, Frac16 f16Speed, ACLIB_BEMF_OBSRV_AB_T *pudtCtrl)

3.3.3 Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*pudtCurrentAlphaBeta</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_ALPHA_BETA_T</td>
<td>N/A</td>
<td>Input signal of alpha/beta current components.</td>
</tr>
<tr>
<td>*pudtVoltageAlphaBeta</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_ALPHA_BETA_T</td>
<td>N/A</td>
<td>Input signal of alpha/beta voltage components.</td>
</tr>
<tr>
<td>f16Speed</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Fraction value of electrical speed.</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_BEMF_OBSRV_AB_T</td>
<td>N/A</td>
<td>Pointer to an observer structure, which contains coefficients.</td>
</tr>
</tbody>
</table>
### Table 3-6. User Types

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>udtEObsrv.f32Alpha</td>
<td>udtEObsrv.f32Alpha</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in beta axis.</td>
</tr>
<tr>
<td>udtEObsrv.f32Beta</td>
<td>udtEObsrv.f32Beta</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in beta axis.</td>
</tr>
<tr>
<td>udtIObsrv.f32Alpha</td>
<td>udtIObsrv.f32Alpha</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated current in alpha axis.</td>
</tr>
<tr>
<td>udtIObsrv.f32Beta</td>
<td>udtIObsrv.f32Beta</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated current in beta axis.</td>
</tr>
<tr>
<td>udtCtrl.f32IAlpha_1</td>
<td>udtCtrl.f32IAlpha_1</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>State variable in alpha part of the observer; integral part at step k-1.</td>
</tr>
<tr>
<td>udtCtrl.f32IBeta_1</td>
<td>udtCtrl.f32IBeta_1</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>State variable in beta part of the observer; integral part at step k-1.</td>
</tr>
<tr>
<td>udtCtrl.f16PropScaled</td>
<td>udtCtrl.f16PropScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer proportional gain.</td>
</tr>
<tr>
<td>udtCtrl.f16IntegScaled</td>
<td>udtCtrl.f16IntegScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer integral gain.</td>
</tr>
<tr>
<td>mcUnityVctr.f16Sin</td>
<td>mcUnityVctr.f16Sin</td>
<td>MCLIB_ANGLE_T</td>
<td>$8000...$7FFF</td>
<td>Sine component of estimated unity vector.</td>
</tr>
<tr>
<td>mcUnityVctr.f16Cos</td>
<td>mcUnityVctr.f16Cos</td>
<td>MCLIB_ANGLE_T</td>
<td>$8000...$7FFF</td>
<td>Cosine component of estimated unity vector.</td>
</tr>
<tr>
<td>f16IScaled</td>
<td>f16IScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for current $I_{FRAC}$.</td>
</tr>
<tr>
<td>f16UScaled</td>
<td>f16UScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for voltage $U_{FRAC}$.</td>
</tr>
<tr>
<td>f16WIScaled</td>
<td>f16WIScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for angular speed $W_{FRAC}$.</td>
</tr>
<tr>
<td>f16EScaled</td>
<td>f16EScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for back-EMF $E_{FRAC}$.</td>
</tr>
</tbody>
</table>

### 3.3.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for 56800E platforms.
### Dependencies

List of all dependent files:

- 56800E_types.h
- 56800E_MCLIB library
- 56800E_GFLIB library
- ACLIB_AngleTrackObsrvAsm.h
- aclib.h

### Description

This back-emf observer is realized within stationary \( \alpha, \beta \) reference frame.

\[
\begin{bmatrix}
    u_{\alpha} \\
    u_{\beta}
\end{bmatrix} =
R_s \begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} +
\begin{bmatrix}
    sL_D & \Delta L \omega_r \\
    -\Delta L_D \omega_r & sL_D
\end{bmatrix} \begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} +
(\Delta L \cdot (\omega_r i_{\alpha} - i_{\beta}') + k_e \omega_r) \begin{bmatrix}
    -\sin(\theta_r) \\
    \cos(\theta_r)
\end{bmatrix}
\]

Eqn. 3-10

where

- \( R_s \) stator resistance
- \( L_d, L_q \) - D-axis and Q-axis inductance
- \( k_e \) back-EMF constant
- \( \omega_r \) rotor angular speed
- \( u_{\alpha}, u_{\beta} \) components of stator voltage vector
- \( i_{\alpha}, i_{\beta} \) components of stator current vector
- \( s \) operator of derivative
- \( i_q' \) first derivative of \( i_q \) current
- \( \Delta L = (L_d - L_q) \) motor saliency

This extended back-EMF model includes both position information from the conventionally defined back-EMF and the stator inductance as well. This allows to extracts the rotor position and velocity information by estimating the extended back EMF only.

Both alpha and beta-axis consists of the stator current observer based on RL motor circuit which requires motor parameters.

The current observer is fed by the sum of the actual applied motor voltage, cross-coupled rotational term, which corresponds to the motor saliency \( (L_d - L_q) \) and compensator corrective output. The observer provides back-EMF signals as disturbance because back-EMF is not included in observer model.
It is obvious that the accuracy of the back EMF estimates is determined by the correctness of used motor parameters (R, L) by fidelity of the reference stator voltage and by quality of compensator such as bandwidth, phase lag and so on.

Appropriate dynamic behavior of the back emf observer is achieved by placement of the poles of the stator current observer characteristic polynomial. This general method is based on matching the coefficients of the characteristic polynomial with the coefficients of the general second-order system.

\[
\dot{E}_{\alpha\beta}(s) = -E_{\alpha\beta}(s) \cdot \left[ \frac{F_c(s)}{sL_d + R_s + F_c(s)} \right]
\]

Eqn. 3-11

Back emf observer is Luenberger type observer with motor model which is realized in fixed point arithmetic transformed using backward Euler transformation.

\[
i_{FRAC(k)} = U_{FRAC} \cdot u_{FRAC(k)} + E_{FRAC} \cdot e_{FRAC(k)} - W_{FRAC} \cdot \omega_{FRAC(k)} \cdot \bar{i}_{FRAC(k)} + i_{FRAC(k-1)}
\]

Eqn. 3-12

where

- \(i_{FRAC(k)} = [i_\alpha, i_\beta]\) is fractional representation of stator current vector
- \(u_{FRAC(k)} = [u_\alpha, u_\beta]\) is fractional representation of stator voltage vector
- \(e_{FRAC(k)} = [e_\alpha, e_\beta]\) is fractional representation of stator back-emf voltage vector
- \(\bar{i}_{FRAC(k)} = [i_\beta, -i_\alpha]\) is fractional representation of complementary stator current vector
- \(\omega_{FRAC(k)}\) is fractional representation of angular speed

Scaling coefficients relating to maximal values are expressed as

\[
U_{FRAC} = \frac{\Delta T_s}{L_d + \Delta T_s R_s} \cdot \frac{U_{MAX}}{I_{MAX}}
\]

Eqn. 3-13
where

- $\Delta T_s$ sampling time in [sec]
- $I_{MAX}$ maximal peak current in [A]
- $E_{MAX}$ maximal peak back-emf voltage in [V]
- $U_{MAX}$ maximal peak stator voltage in [V]
- $\Omega_{MAX}$ maximal angular speed in [rad/sec]

If a Luenberger type stator current observer is properly designed in the stationary reference frame, the back-EMF can be estimated as a disturbance, produced by the observer controller. This is only valid however if the back-EMF term is not included in the observer model. The observer is actually a closed loop current observer so it acts as a state filter for the back-EMF term.

The estimate of extended EMF term can be derived from Equation 3-11 as follows:

$$E_{FRAC} = \frac{\Delta T_s}{L_d + \Delta T_s R_s} \cdot \frac{E_{MAX}}{I_{MAX}}$$  
Eqn. 3-14

$$WI_{FRAC} = \frac{\Delta L \cdot \Delta T_s}{L_d + \Delta T_s R_s} \cdot \Omega_{MAX}$$  
Eqn. 3-15

$$I_{FRAC} = \frac{L_d}{L_d + \Delta T_s R_s}$$  
Eqn. 3-16

The observer controller can be designed by comparing the closed loop characteristic polynomial with that of a standard second order system as:

$$\frac{\hat{E}_{ab}(s)}{E_{ab}(s)} = \frac{s K_p + K_i}{s^2 L_D + s R_S + s K_p + K_I}$$  
Eqn. 3-17

$$\frac{s^2 + \frac{K_p}{L_D} \cdot s + \frac{K_I}{L_D}}{s^2 + 2 \xi \omega_0 s + \omega_0^2} = s^2 + 2 \xi \omega_0 s + \omega_0^2$$  
Eqn. 3-18

where

- $\omega_0$ is the natural frequency of the closed loop system (loop bandwidth)
- $\xi$ is the loop attenuation.

### 3.3.7 Returns

The function returns a unity vector representing the estimated value of sine and cosine values of back emf.
3.3.8 Implementation

Example 3-2. Implementation Code

```c
#include "gflib.h"
#include "mclib.h"
#include "aclib.h"

MCLIB_2_COOR_SYST_ALPHA_BETA_T mcI, mcU;
ACLIB_BEMF_OBSRV_AB_T acBemfObsrv;

void Isr(void);

void main (void)
{
    acBemfObsrv.udtEObsrv.f32Alpha = FRAC32(0.0);
    acBemfObsrv.udtEObsrv.f32Beta = FRAC32(0.0);
    acBemfObsrv.udtIObsrv.f32Alpha = FRAC32(0.0);
    acBemfObsrv.udtIObsrv.f32Beta = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f32IAlpha_1 = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f32IBeta_1 = FRAC32(0.0);
    acBemfObsrv.udtCtrl.f16PropScaled = BEMFOBSRV_AB_PROP_GAIN_SCALED;
    acBemfObsrv.udtCtrl.i16PropShift = BEMFOBSRV_AB_PROP_GAIN_SHIFT;
    acBemfObsrv.udtCtrl.f16IntegScaled = BEMFOBSRV_AB_INTEG_GAIN_SCALED;
    acBemfObsrv.udtCtrl.i16IntegShift = BEMFOBSRV_AB_INTEG_GAIN_SHIFT;
    acBemfObsrv.f16IScaled = BEMFOBSRV_AB_I_SCALED;
    acBemfObsrv.f16UScaled = BEMFOBSRV_AB_U_SCALED;
    acBemfObsrv.f16EScaled = BEMFOBSRV_AB_E_SCALED;
    acBemfObsrv.f16WIScaled = BEMFOBSRV_AB_WI_SCALED;
}

/* Periodical function or interrupt */
void ISR(void)
{
    ACLIB_PMSMBemfObsrv12AB(&mcI,&mcU,f16Speed,&acBemfObsrv);
}
```

3.3.9 Performance

Table 3-7. Performance of ACLIB_PMSMBemfObsrv12AB function

<table>
<thead>
<tr>
<th>Code Size (words)</th>
<th>167 + 28 (GFLIB_SqrtIter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Size (words)</td>
<td>0</td>
</tr>
<tr>
<td>Execution Clock</td>
<td>Min 301/282 cycles</td>
</tr>
<tr>
<td></td>
<td>Max 301/282 cycles</td>
</tr>
</tbody>
</table>

Advanced Control Library, Rev. 2
3.4 ACLIB_AngleTrackObsrv

The function calculates angle tracking observer for determination angular speed and position of input functional signal.

3.4.1 Synopsis

```c
#include "aclib.h"
Frac16 ACLIB_AngleTrackObsrv(MCLIB_ANGLE_T *pudtSinCos,
ACLIB_ANGLE_TRACK_OBSRV_T * pudtCtrl)
```

3.4.2 Prototype

```c
asm Frac16 ACLIB_AngleTrackObsrvFAsm(MCLIB_ANGLE_T *pudtSinCos,
ACLIB_ANGLE_TRACK_OBSRV_T * const pudtCtrl)
```

3.4.3 Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*pudtSinCos</td>
<td>in</td>
<td>MCLIB_ANGLE_T</td>
<td>N/A</td>
<td>input signal of sine, cosine components to be filtered</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_ANGLE_TRACK_OBSRV_T</td>
<td>N/A</td>
<td>pointer to an angle tracking observer structure ACLIB_ANGLE_TRACK_OBSRV_T, which contains algorithm coefficients</td>
</tr>
</tbody>
</table>
### 3.4.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for 56800E platforms.

### 3.4.5 Dependencies

List of all dependent files:
- 56800E_types.h
- 56800E_MCLIB library
- 56800E_GFLIB library
- ACLIB_AngleTrackObsrvAsm.h
- aclib.h

---

#### Table 3-9. User type definitions

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCLIB_ANGLE_T</td>
<td>f16Sin</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>sine component to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16Cos</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>cosine component to be estimated</td>
</tr>
<tr>
<td></td>
<td>f32Speed</td>
<td>in/out</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Estimated speed as output of the first numerical integrator</td>
</tr>
<tr>
<td></td>
<td>f32A2</td>
<td>in/out</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Output of the second numerical integrator</td>
</tr>
<tr>
<td></td>
<td>f16Theta</td>
<td>in/out</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Estimated position</td>
</tr>
<tr>
<td></td>
<td>f16SinEstim</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Sine signal to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16CosEstim</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Cosine signal to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16K1Scaled</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>K1 coefficient scaled to fractional range</td>
</tr>
<tr>
<td></td>
<td>i16K1Shift</td>
<td>in</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
<tr>
<td></td>
<td>f16K2Scaled</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>K2 coefficient scaled to fractional range</td>
</tr>
<tr>
<td></td>
<td>i16K2Shift</td>
<td>in</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
<tr>
<td></td>
<td>f16A2Scaled</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient due to numerical integration</td>
</tr>
<tr>
<td></td>
<td>i16A2Shift</td>
<td>in</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
</tbody>
</table>
3.4.6 Description

This function calculates the angle tracking observer algorithm. It is recommended to call this function at every sampling period. It requires two input arguments as sine and cosine samples. The practical implementation of the angle tracking observer algorithm is described below.

The angle tracking observer compares values of the input signals \( \sin(\theta) \), \( \cos(\theta) \) with their corresponding estimations \( \sin(\hat{\theta}) \), \( \cos(\hat{\theta}) \). As in any common closed-loop systems, the intent is to minimize observer error towards zero value. The observer error is given here by subtraction of the estimated resolver rotor angle \( \hat{\theta} \) from the actual rotor angle \( \theta \) (see Figure 3-3).

![Block scheme of the angle tracking observer](image)

**Figure 3-3. Block scheme of the angle tracking observer**

Note that mathematical expression of observer error is known as the formula of the difference of two angles:

\[
\sin(\theta - \hat{\theta}) = \sin(\theta) \cdot \cos(\hat{\theta}) - \cos(\theta) \cdot \sin(\hat{\theta})
\]

*Eqn. 3-19*

In the case of minimal deviations out of the estimated rotor angle compared to the actual rotor angle, the observer error may be expressed in the following form

\[
\sin(\theta - \hat{\theta}) = \theta - \hat{\theta}
\]

*Eqn. 3-20*

The primary benefit of the angle tracking observer utilization, in comparison with the trigonometric method, is its smoothing capability. This filtering is achieved by the integrator and proportional and integral controller, which are connected in series and closed by a unit feedback loop. This block diagram nicely tracks actual rotor angle and speed and continuously updates their estimations. The angle tracking observer transfer function is expressed as follows

\[
\frac{\hat{\theta}(s)}{\theta(s)} = \frac{K_1(1 + K_2s)}{s^2 + K_1K_2s + K_1}
\]

*Eqn. 3-21*

The characteristic polynomial of the angle tracking observer corresponds to the denominator of transfer function

\[
s^2 + K_1K_2s + K_1
\]

*Eqn. 3-22*
Appropriate dynamic behavior of the angle tracking observer is achieved by placement of the poles of the characteristic polynomial. This general method is based on matching the coefficients of the characteristic polynomial with the coefficients of the general second-order system.

The analog integrators in Figure 3-1, marked as $\frac{1}{s}$ are replaced by an equivalent of the discrete-time integrator using the backward Euler integration method. The discrete-time block diagram of the angle tracking observer is shown in Figure 3-4.

The essential equations for implementation of the angle tracking observer, according to block scheme in Figure 3-4, are as follows:

\begin{align*}
e(k) &= \sin(k) \cdot \cos(\dot{\theta}(k)) - \cos(k) \cdot \sin(\dot{\theta}(k)) & \text{Eqn. 3-23} \\
o(k) &= \omega(k-1) + K_1 \cdot \Delta T_s \cdot e(k) & \text{Eqn. 3-24} \\
a_2(k) &= a_2(k-1) + \Delta T_s \cdot \omega(k) & \text{Eqn. 3-25} \\
\dot{\theta}(k) &= K_2 \cdot \omega(k) + a_2(k) & \text{Eqn. 3-26}
\end{align*}

In equations Equation 3-23 to Equation 3-26, there are coefficients and quantities that might be greater than one (for example, the actual rotor speed $\omega(k)$) or that are too small to be precisely represented within 16-bit fractional value. Due to this fact a special transformation of equations Equation 3-23 to Equation 3-26 have to be carried out in order to be successfully implemented using fractional arithmetic.

\begin{align*}
K_{1FRAC} &= \Delta T_s \cdot \frac{K_1}{\Omega_{MAX}} & \text{Eqn. 3-27} \\
K_{2FRAC} &= K_2 \cdot \frac{\Omega_{MAX}}{\Theta_{MAX}} & \text{Eqn. 3-28} \\
A_{2FRAC} &= \Delta T_s \cdot \frac{\Omega_{MAX}}{\Theta_{MAX}} & \text{Eqn. 3-29}
\end{align*}
where the variables of the angle tracking observer are

- $e(k)$ is observer error in step $k$,
- $\Delta T_s$ is the sampling period [s],
- $\omega(k)$ is the actual rotor speed [rad/s] in step $k$,
- $\theta(k)$ is the actual rotor angle [rad] in step $k$,
- $\theta_2(k)$ is the actual rotor angle [rad] without scaled addition of speed in step $k$.

The scaled coefficients which are suitable for implementation on the DSP core are as follows:

$$f16K1Scaled = K_{1_{FRAC}} \cdot 2^{-i16K1Shift} \quad \text{Eqn. 3-30}$$

$$f16K2Scaled = K_{2_{FRAC}} \cdot 2^{-i16K2Shift} \quad \text{Eqn. 3-31}$$

$$f16A2Scaled = A_{2_{FRAC}} \cdot 2^{-i16A2Shift} \quad \text{Eqn. 3-32}$$

3.4.7 Return

The function returns an estimation of the actual rotor angle as 16 bit fractional value.

3.4.8 Range Issues

The function works with the 16-bit signed fractional values in the range $<-1,1)$.

3.4.9 Special Issues

The ACLIB.AngleTrackObsrv function requires the saturation mode to be turned on.

3.4.10 Implementation

**Example 3-3. implementation Code**

```c
#include "gflib.h"
#include "mclib.h"
#include "aclib.h"

MCLIB_ANGLE_T mcAngle;
ACLIB_ANGLE_TRACK_OBSRV_T acAngleTrackObsrv;
Frac16 f16PositionOut;

void main (void)
{
    acAngleTrckObsrv.f32Speed = FRAC32(0);
}
```

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ACLIB_AngleTrackObsrv

```c
acAngleTrckObsrv.f32A2 = FRAC32(0);
acAngleTrckObsrv.f16Theta = FRAC16(0);
acAngleTrckObsrv.f16SinEstim = FRAC16(0);
acAngleTrckObsrv.f16CosEstim = FRAC16(0);
acAngleTrckObsrv.f16K1Scaled = ANGLETRACKOBSRV_K1_SCALED;
acAngleTrckObsrv.i16K1Shift = ANGLETRACKOBSRV_K1_SHIFT;
acAngleTrckObsrv.f16K2Scaled = ANGLETRACKOBSRV_K2_SCALED;
acAngleTrckObsrv.i16K2Shift = ANGLETRACKOBSRV_K2_SHIFT;
acAngleTrckObsrv.f16A2Scaled = ANGLETRACKOBSRV_A2_SCALED;
acAngleTrckObsrv.i16A2Shift = ANGLETRACKOBSRV_A2_SHIFT;
```

} /* Periodical function or interrupt */

```c
ISR(void)
{
    f16PositionOut = ACLIB_AngleTrackObsrv(&mcAngle, &acAngleTrackObsrv);
}
```

## 3.4.11 Performance

### Table 3-10. Performance of ACLIB_AngleTrackObsrv function

<table>
<thead>
<tr>
<th>Code Size (words)</th>
<th>78 + 38 (GFLIB_SinTlr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Size (words)</td>
<td>0 + 10 (GFLIB_SinTlr)</td>
</tr>
<tr>
<td>Execution Clock</td>
<td>Min 196/183 cycles</td>
</tr>
<tr>
<td></td>
<td>Max 196/183 cycles</td>
</tr>
</tbody>
</table>
3.5 ACLIB_AngleTrackObsrv12

The function calculates angle tracking observer for determination angular speed and position of input functional signal. This version uses the quicker 12-bit precision sine calculation therefore it is quicker but with reduced precision in comparison to ACLIB_AngleTrackObsrv.

3.5.1 Synopsis

```c
#include"aclib.h"
Frac16 ACLIB_AngleTrackObsrv12(MCLIB_ANGLE_T *pudtSinCos,
ACLIB_ANGLE_TRACK_OBSRV_T * pudtCtrl)
```

3.5.2 Prototype

```asm
asm Frac16 ACLIB_AngleTrackObsrv12FAsm(MCLIB_ANGLE_T *pudtSinCos,
ACLIB_ANGLE_TRACK_OBSRV_T * const pudtCtrl)
```

3.5.3 Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*pudtSinCos</td>
<td>in</td>
<td>MCLIB_ANGLE_T</td>
<td>N/A</td>
<td>input signal of sine, cosine components to be filtered</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_ANGLE_TRACK_OBSRV_T</td>
<td>N/A</td>
<td>pointer to an angle tracking observer structure ACLIB_ANGLE_TRACK_OBSRV_T, which contains algorithm coefficients</td>
</tr>
</tbody>
</table>
### Table 3-12. User type definitions

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCLIB_ANGLE_T</td>
<td>f16Sin</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>sine component to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16Cos</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>cosine component to be estimated</td>
</tr>
<tr>
<td></td>
<td>f32Speed</td>
<td>In/Out</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Estimated speed as output of the first numerical integrator</td>
</tr>
<tr>
<td></td>
<td>f32A2</td>
<td>In/Out</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFF</td>
<td>Output of the second numerical integrator</td>
</tr>
<tr>
<td></td>
<td>f16Theta</td>
<td>In/Out</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Estimated position</td>
</tr>
<tr>
<td></td>
<td>f16SinEstim</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Sine signal to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16CosEstim</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Cosine signal to be estimated</td>
</tr>
<tr>
<td></td>
<td>f16K1Scaled</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>K1 coefficient scaled to fractional range</td>
</tr>
<tr>
<td></td>
<td>i16K1Shift</td>
<td>In</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
<tr>
<td></td>
<td>f16K2Scaled</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>K2 coefficient scaled to fractional range</td>
</tr>
<tr>
<td></td>
<td>i16K2Shift</td>
<td>In</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
<tr>
<td></td>
<td>f16A2Scaled</td>
<td>In</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient due to numerical integration</td>
</tr>
<tr>
<td></td>
<td>i16A2Shift</td>
<td>In</td>
<td>SI16</td>
<td>-F...F</td>
<td>Scaling shift</td>
</tr>
<tr>
<td>ACLIB_ANGLE_TRACK_OBSRV_T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.5.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for 56800E platforms.

#### 3.5.5 Dependencies

List of all dependent files:

- 56800E_types.h
- 56800E_MCLIB library
- 56800E_GFLIB library
- ACLIB_AngleTrackObsrvAsm.h
- aclib.h
3.5.6 Description

This function calculates the angle tracking observer algorithm. It is recommended to call this function at every sampling period. It requires two input arguments as sine and cosine samples. The practical implementation of the angle tracking observer algorithm is described below.

The angle tracking observer compares values of the input signals \( \sin(\theta) \), \( \cos(\theta) \) with their corresponding estimations \( \sin(\hat{\theta}) \), \( \cos(\hat{\theta}) \). As in any common closed-loop systems, the intent is to minimize observer error towards zero value. The observer error is given here by subtraction of the estimated resolver rotor angle \( \hat{\theta} \) from the actual rotor angle \( \theta \) (see Figure 3-5).

\[
\text{Figure 3-5. Block scheme of the angle tracking observer}
\]

Note that mathematical expression of observer error is known as the formula of the difference of two angles:

\[
\sin(\theta - \hat{\theta}) = \sin(\theta) \cdot \cos(\hat{\theta}) - \cos(\theta) \cdot \sin(\hat{\theta})
\]

**Eqn. 3-33**

In the case of minimal deviations out of the estimated rotor angle compared to the actual rotor angle, the observer error may be expressed in the following form

\[
\sin(\theta - \hat{\theta}) = \theta - \hat{\theta}
\]

**Eqn. 3-34**

The primary benefit of the angle tracking observer utilization, in comparison with the trigonometric method, is its smoothing capability. This filtering is achieved by the integrator and proportional and integral controller, which are connected in series and closed by a unit feedback loop. This block diagram nicely tracks actual rotor angle and speed and continuously updates their estimations. The angle tracking observer transfer function is expressed as follows

\[
\frac{\hat{\theta}(s)}{\theta(s)} = \frac{K_1(1 + K_2s)}{s^2 + K_1K_2s + K_1}
\]

**Eqn. 3-35**

The characteristic polynomial of the angle tracking observer corresponds to the denominator of transfer function

\[
s^2 + K_1K_2s + K_1
\]

**Eqn. 3-36**
Appropriate dynamic behavior of the angle tracking observer is achieved by placement of the poles of the characteristic polynomial. This general method is based on matching the coefficients of the characteristic polynomial with the coefficients of the general second-order system.

The analog integrators in Figure 3-1, marked as $1/s$ are replaced by an equivalent of the discrete-time integrator using the backward Euler integration method. The discrete-time block diagram of the angle tracking observer is shown in Figure 3-6.

![Figure 3-6. Block scheme of discrete-time tracking observer](image)

The essential equations for implementation of the angle tracking observer, according to block scheme in Figure 3-6, are as follows:

1. $e(k) = \sin(k) \cdot \cos(\tilde{\theta}(k)) - \cos(k) \cdot \sin(\tilde{\theta}(k)) \quad Eqn. 3-37$
2. $\omega(k) = \omega(k-1) + K_1 \cdot \Delta T_s \cdot e(k) \quad Eqn. 3-38$
3. $a_2(k) = a_2(k-1) + \Delta T_s \cdot \omega(k) \quad Eqn. 3-39$
4. $\theta(k) = K_2 \cdot \omega(k) + a_2(k) \quad Eqn. 3-40$

In equations Equation 3-37 to Equation 3-40, there are coefficients and quantities that might be greater than one (for example, the actual rotor speed $\omega(k)$) or that are too small to be precisely represented within 16-bit fractional value. Due to this fact a special transformation of equations Equation 3-37 to Equation 3-40 have to be carried out in order to be successfully implemented using fractional arithmetic.

1. $K_{1FRAC} = \Delta T_s \cdot \frac{K_1}{\Omega_{MAX}} \quad Eqn. 3-41$
2. $K_{2FRAC} = K_2 \cdot \frac{\Omega_{MAX}}{\Theta_{MAX}} \quad Eqn. 3-42$
3. $A_{2FRAC} = \Delta T_s \cdot \frac{\Omega_{MAX}}{\Theta_{MAX}} \quad Eqn. 3-43$
where the variables of the angle tracking observer are

- $e(k)$ is observer error in step $k$,
- $\Delta T_s$ is the sampling period [s],
- $\omega(k)$ is the actual rotor speed [rad/s] in step $k$,
- $\theta(k)$ is the actual rotor angle [rad] in step $k$,
- $a_2(k)$ is the actual rotor angle [rad] without scaled addition of speed in step $k$.

The scaled coefficients which are suitable for implementation on the DSP core are as follows:

$$f_{16K1\text{Scaled}} = K_{1\text{FRAC}} \cdot 2^{-i16K1\text{Shift}} \quad \text{Eqn. 3-44}$$

$$f_{16K2\text{Scaled}} = K_{2\text{FRAC}} \cdot 2^{-i16K2\text{Shift}} \quad \text{Eqn. 3-45}$$

$$f_{16A2\text{Scaled}} = A_{2\text{FRAC}} \cdot 2^{-i16A2\text{Shift}} \quad \text{Eqn. 3-46}$$

### 3.5.7 Return

The function returns an estimation of the actual rotor angle as 16 bit fractional value.

### 3.5.8 Range Issues

The function works with the 16-bit signed fractional values in the range $<-1,1)$.

### 3.5.9 Special Issues

The `ACLIB_AngleTrackObsrv12` function requires the saturation mode to be turned on.

### 3.5.10 Implementation

**Example 3-4. implementation Code**

```c
#include "gflib.h"
#include "mclib.h"
#include "aclib.h"

MCLIB_ANGLE_T mcAngle;
ACLIB_ANGLE_TRACK_OBSRV_T acAngleTrackObsrv;
Frac16 f16PositionOut;

void main (void)
{
    acAngleTrckObsrv.f32Speed = FRAC32(0);
```

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```c
acAngleTrckObsrv.f32A2 = FRAC32(0);
acAngleTrckObsrv.f16Theta = FRAC16(0);
acAngleTrckObsrv.f16SinEstim = FRAC16(0);
acAngleTrckObsrv.f16CosEstim = FRAC16(0);
acAngleTrckObsrv.f16K1Scaled = ANGLETRACKOBSRV_K1_SCALED;
acAngleTrckObsrv.i16K1Shift = ANGLETRACKOBSRV_K1_SHIFT;
acAngleTrckObsrv.f16K2Scaled = ANGLETRACKOBSRV_K2_SCALED;
acAngleTrckObsrv.i16K2Shift = ANGLETRACKOBSRV_K2_SHIFT;
acAngleTrckObsrv.f16A2Scaled = ANGLETRACKOBSRV_A2_SCALED;
acAngleTrckObsrv.i16A2Shift = ANGLETRACKOBSRV_A2_SHIFT;
```

```c
ISR(void)
{
    f16PositionOut = ACLIB_AngleTrackObsrv12(&mcAngle, &acAngleTrackObsrv);
}
```

### 3.5.11 Performance

Table 3-13. Performance of ACLIB_AngleTrackObsrv12 function

<table>
<thead>
<tr>
<th></th>
<th>Code Size (words)</th>
<th>Data Size (words)</th>
<th>Execution Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>78 + 25 (GFLIB_Sin12Tlr)</td>
<td>0 + 5 (GFLIB_Sin12Tlr)</td>
<td>Min 168/156 cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max 168/156 cycles</td>
</tr>
</tbody>
</table>
3.6 ACLIB_PMSMBemfObsrvDQ

The function calculates the algorithm of back electro-motive force observer in rotating reference frame.

3.6.1 Synopsis

#include "aclib.h"
void ACLIB_PMSMBemfObsrvDQ(MCLIB_2_COOR_SYST_D_Q_T *pudtCurrentDQ,
MCLIB_2_COOR_SYST_D_Q_T *pudtVoltageDQ, Frac16 f16Speed,
ACLIB_BEMF_OBSRV_DQ_T *pudtCtrl)

3.6.2 Prototype

asm void ACLIB_PMSMBemfObsrvDQFAsm(MCLIB_2_COOR_SYST_D_Q_T
*pudtCurrentDQ, MCLIB_2_COOR_SYST_D_Q_T *pudtVoltageDQ, Frac16 f16Speed,
ACLIB_BEMF_OBSRV_DQ_T *pudtCtrl)

3.6.3 Arguments

Table 3-14. Function Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>*pudtCurrentDQ</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_D_Q_T</td>
<td>N/A</td>
<td>pointer to structure which contain input signal of d/q current components</td>
</tr>
<tr>
<td>*pudtVoltageDQ</td>
<td>in</td>
<td>MCLIB_2_COOR_SYST_D_Q_T</td>
<td>N/A</td>
<td>pointer to structure which contain input signal of d/q voltage components</td>
</tr>
<tr>
<td>f16Frac</td>
<td>in/out</td>
<td>SF16</td>
<td>N/A</td>
<td>Fraction value of electrical speed.</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_BEMF_OBSRV_DQ_T</td>
<td>N/A</td>
<td>Pointer to an observer structure, which contains coefficients.</td>
</tr>
</tbody>
</table>
### Table 3-15. User Types

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>udtEObsrv.f32D</td>
<td>udtEObsrv.f32D</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in d-axis</td>
</tr>
<tr>
<td>udtEObsrv.f32Q</td>
<td>udtEObsrv.f32Q</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Estimated back-EMF voltage in q-axis</td>
</tr>
<tr>
<td>udtIObsrv.f32D</td>
<td>udtIObsrv.f32D</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Estimated current in d-axis</td>
</tr>
<tr>
<td>udtIObsrv.f32Q</td>
<td>udtIObsrv.f32Q</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>Estimated current in q-axis</td>
</tr>
<tr>
<td>udtCtrl.f32ID_1</td>
<td>udtCtrl.f32ID_1</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>State variable in alpha part of the observer; integral part at step k-1;</td>
</tr>
<tr>
<td>udtCtrl.f32IQ_1</td>
<td>udtCtrl.f32IQ_1</td>
<td>SF32</td>
<td>0x800000000...0x7FFFFFF</td>
<td>State variable in beta part of the observer; integral part at step k-1;</td>
</tr>
<tr>
<td>udtCtrl.f16PropScaled</td>
<td>udtCtrl.f16PropScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer proportional gain</td>
</tr>
<tr>
<td>udtCtrl.i16PropShift</td>
<td>udtCtrl.i16PropShift</td>
<td>SI16</td>
<td>-F...F</td>
<td>Observer proportional gain shift</td>
</tr>
<tr>
<td>udtCtrl.f16IntegScaled</td>
<td>udtCtrl.f16IntegScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer integral gain</td>
</tr>
<tr>
<td>udtCtrl.i16IntegShift</td>
<td>udtCtrl.i16IntegShift</td>
<td>SI16</td>
<td>-F...F</td>
<td>Observer integral gain shift</td>
</tr>
<tr>
<td>f16Error</td>
<td>f16Error</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Estimated phase error between real d/q frame system and estimated d/q reference system</td>
</tr>
<tr>
<td>f16IScaled</td>
<td>f16IScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for current $i_{FRAC}$</td>
</tr>
<tr>
<td>f16UScaled</td>
<td>f16UScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for voltage $U_{FRAC}$</td>
</tr>
<tr>
<td>f16WIScaled</td>
<td>f16WIScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for angular speed $W_{FRAC}$</td>
</tr>
<tr>
<td>f16EScaled</td>
<td>f16EScaled</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for back-emf $E_{FRAC}$</td>
</tr>
</tbody>
</table>

#### 3.6.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for 56800E platforms.

#### 3.6.5 Dependencies

List of all dependent files:
- 56800E_types.h
3.6.6 Description

The estimation method for the rotor position and angular speed is based on the motor mathematical model of interior PMSM motor with an extended electro-motive force function which is realized in estimated quasi synchronous reference frame \( \gamma \delta \) as depicted on Figure 3-7.

![Figure 3-7. Estimated \( \gamma \delta \) and real rotor \( dq \) synchronous reference frames](image)

The back-EMF observer detects the generated motor voltages induced by the permanent magnets. A tracking observer uses the back-EMF signals to calculate the position and speed of the rotor. The transformed model is then derived as follows:

\[
\begin{bmatrix}
    u_\gamma \\
    u_\delta
\end{bmatrix} = 
\begin{bmatrix}
    R_s + sL_D - \omega_r L_Q & -\omega_r L_Q \\
    \omega_r L_Q & R_s + sL_Q
\end{bmatrix} 
\begin{bmatrix}
    i_\gamma \\
    i_\delta
\end{bmatrix} + 
\begin{bmatrix}
    \omega_r \left( Q_e i_D - i_Q' \right) + k_e \omega_e \cdot 
    \begin{bmatrix}
        \sin(\theta_{error}) \\
        \cos(\theta_{error})
    \end{bmatrix}
\end{bmatrix}
\]

\text{Eqn. 3-47}

where

- \( R_s \) stator resistance
- \( L_D, L_Q \) - D-axis and Q-axis inductance
- \( k_e \) back-EMF constant
- \( \omega_e \) angular electrical speed
- \( u_D, u_Q \) stator voltages
- \( i_D, i_Q \) stator currents
- \( s \) operator of derivative
- \( i_q' \) - first derivative of \( i_q \) current

Block diagram of the observer in the estimated reference frame is shown on Figure 3-8. The observer compensator is substituted by a standard PI controller. As can be noted from Figure 3-8, observer model and hence also PI controller gains in both axis are identical to each other.
The position estimation can now be performed by extracting the $\theta_{error}$ term from the model and adjusting the position of the estimated reference frame such as to achieve $\theta_{error} = 0$. Because the $\theta_{error}$ term is only included in the saliency-based EMF component of both $u_\gamma$, $u_\delta$ axis voltage equations, the Luenberger based disturbance observer is designed to observe these voltage components $u_\gamma$, $u_\delta$. The position displacement information $\theta_{error}$ is then obtained from estimated back-EMFs as follows:

$$\theta_{error} = \text{atan}\left(\frac{-u_\delta}{u_\gamma}\right)$$  \hspace{1cm} \text{Eqn. 3-48}

The estimated position $\hat{\theta}$ can be obtained by driving the position of the estimated reference frame such as to achieve zero displacement $\theta_{error} = 0$. The phase locked loop mechanism can be adopted, where the loop compensator ensures correct tracking of the actual rotor flux position by keeping the error signal $\theta_{error}$ to be zeroed, $\theta_{error} = 0$.

A perfect match between the actual and estimated motor model parameters is assumed, and then back-EMF transfer function is simplified as follows

$$\dot{E}_{ab}(s) = -E_{ab}(s) \cdot \frac{F_c(s)}{sL_D + R_S + F_c(s)}$$  \hspace{1cm} \text{Eqn. 3-49}

Appropriate dynamic behavior of the back emf observer is achieved by placement of the poles of the stator current observer characteristic polynomial. This general method is based on matching the coefficients of the characteristic polynomial with the coefficients of the general second-order system.

Back emf observer is Luenberger type observer with motor model which is realized in fixed point arithmetic transformed using backward Euler transformation.
\[ i_{\text{FRFAC}}(k) = U_{\text{FRAC}} \cdot u_{\text{FRAC}}(k) + E_{\text{FRAC}} \cdot e_{\text{FRAC}}(k) + W I_{\text{FRAC}} \cdot \omega_{\text{FRAC}}(k) \cdot i_{\text{FRAC}}(k) + I_{\text{FRAC}} \cdot i_{\text{FRAC}}(k-1) \]  

\text{Eqn. 3-50}

where

- \( i_{\text{FRFAC}}(k) = [i_p \ i_b] \) is fractional representation of stator current vector
- \( u_{\text{FRAC}}(k) = [u_p \ u_b] \) is fractional representation of stator voltage vector
- \( e_{\text{FRAC}}(k) = [e_p \ e_b] \) is fractional representation of stator back-emf voltage vector
- \( i_{\text{FRFAC}}(k) = [i_b - i_p] \) is fractional representation of complementary stator current vector
- \( \omega_{\text{FRAC}}(k) \) is fractional representation of angular speed

Scaling coefficients relating to maximal values are expressed as

\[ U_{\text{FRAC}} = \frac{\Delta T_S}{L_D + \Delta T_S R_S} \cdot \frac{U_{\text{MAX}}}{I_{\text{MAX}}} \]  

\text{Eqn. 3-51}

\[ E_{\text{FRAC}} = \frac{\Delta T_S}{L_D + \Delta T_S R_S} \cdot \frac{E_{\text{MAX}}}{I_{\text{MAX}}} \]  

\text{Eqn. 3-52}

\[ W_{\text{FRAC}} = \frac{L_Q \cdot \Delta T_S}{L_D + \Delta T_S R_S} \cdot \Omega_{\text{MAX}} \]  

\text{Eqn. 3-53}

\[ I_{\text{FRAC}} = \frac{L_D}{L_D + \Delta T_S R_S} \]  

\text{Eqn. 3-54}

where

- \( \Delta T_S \) sampling time in [sec]
- \( I_{\text{MAX}} \) maximal peak current in [A]
- \( E_{\text{MAX}} \) maximal peak back-emf voltage in [V]
- \( U_{\text{MAX}} \) maximal peak stator voltage in [V]
- \( \Omega_{\text{MAX}} \) maximal angular speed in [rad/sec]

If a Luenberger type stator current observer is properly designed in the stationary reference frame, the back-EMF can be estimated as a disturbance, produced by the observer controller. This is only valid however if the back-EMF term is not included in the observer model. The observer is actually a closed loop current observer so it acts as a state filter for the back-EMF term.

The estimate of extended EMF term can be derived from 

\[ \tilde{E}_{\gamma}(s) = \frac{s K_p + K_i}{s^2 L_D + s R_S + s K_p + K_i} \]  

\text{Eqn. 3-55}

\( \tilde{E}_{\gamma}(s) \) is the estimated back-emf term, \( E_{\gamma}(s) \) is the actual back-emf term, and \( s, K_p, K_i \) are the Laplace transform variable and gain used in the observer controller.
The observer controller can be designed by comparing the closed loop characteristic polynomial with that of a standard second order system as:

\[ s^2 \frac{K_P + R_S}{L_D} \cdot s + \frac{K_I}{L_D} = s^2 + 2\zeta\omega_0 s + \omega_0^2 \]

Eqn. 3-56

where

- \( \omega_0 \) is the natural frequency of the closed loop system (loop bandwith)
- \( \zeta \) is the loop attenuation.

### 3.6.7 Returns

The function returns a phase error between real rotating reference frame and estimated one.

### 3.6.8 Range Issues

The function works with the 16-bit signed fractional values in the range <-1,1>.

### 3.6.9 Special Issues

The ACLIB_PMSMBemfObsrvDQ function requires the saturation mode to be turned on.

### 3.6.10 Implementation

Example 3-5. Implementation Code

```c
#include "gfplib.h"
#include "mclib.h"
#include "aclib.h"

MCLIB_2_COOR_SYST_D_Q_T mcIdq, mcUdq;
ACLIB_BEMF_OBSRV_DQ_T acBemfObsrv;
Frac16 f16Speed;

void main (void) {

acBemfObsrv.udtIObsrv.f32D = FRAC32(0.0);
acBemfObsrv.udtIObsrv.f32Q = FRAC32(0.0);
acBemfObsrv.udtEObsrv.f32D = FRAC32(0.0);
acBemfObsrv.udtEObsrv.f32Q = FRAC32(0.0);
acBemfObsrv.udtCtrl.f32ID_1= FRAC32(0.0);
acBemfObsrv.udtCtrl.f32IQ_1= FRAC32(0.0);
acBemfObsrv.udtCtrl.f16PropScaled= BEMFOBSRV_DQ_PROP_GAIN_SCALED;
acBemfObsrv.udtCtrl.i16PropShift= BEMFOBSRV_DQ_PROP_GAIN_SHIFT;
acBemfObsrv.udtCtrl.f16IntegScaled= BEMFOBSRV_DQ_INTEG_GAIN_SCALED;
acBemfObsrv.udtCtrl.i16IntegShift = BEMFOBSRV_DQ_INTEG_GAIN_SHIFT;
acBemfObsrv.f16IScaled = BEMFOBSRV_DQ_I_SCALED;
```

Advanced Control Library, Rev. 2
ACLIB_PMSMBemfObsrvDQ

```c
acBemfObsrv.f16UScaled = BEMFOBSRV_DQ_U_SCALED;
acBemfObsrv.f16EScaled = BEMFOBSRV_DQ_E_SCALED;
acBemfObsrv.f16WIScaled = BEMFOBSRV_DQ_WI_SCALED;
}

/* Periodical function or interrupt */
void ISR(void)
{
    ACLIB_PMSMBemfObsrvDQ(&mcIdq, &mcUdq, f16Speed, &acBemfObsrv);
}
```

### 3.6.11 Performance

#### Table 3-16. Performance of ACLIB_PMSMBemfObsrvDQ function

<table>
<thead>
<tr>
<th>Code Size (words)</th>
<th>145 + 100 (GFLIB_AtanYX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Size (words)</td>
<td>0 + 33 (GFLIB_AtanYX)</td>
</tr>
<tr>
<td>Execution Clock</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>225/204 cycles</td>
</tr>
<tr>
<td>Max</td>
<td>301/277 cycles</td>
</tr>
</tbody>
</table>
3.7 ACLIB_TrackObsrv

The function calculates tracking observer for determination angular speed and position of input error functional signal.

3.7.1 Synopsis

```c
#include "aclib.h"
Frac16 ACLIB_TrackObsrv(Frac16 f16Error, ACLIB_TRACK_OBSRV_T *pudtCtrl)
```

3.7.2 Prototype

```c
asm Frac16 ACLIB_TrackObsrvFAsm(Frac16 f16Error, ACLIB_TRACK_OBSRV_T *pudtCtrl)
```

3.7.3 Arguments

Table 3-17. Function Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f16Error</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>input signal representing phase error of system to be estimated</td>
</tr>
<tr>
<td>*pudtCtrl</td>
<td>in/out</td>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>N/A</td>
<td>pointer to a racking observer structure ACLIB_TRACK_OBSRV_T, which contains algorithm coefficients</td>
</tr>
</tbody>
</table>
3.7.4 Availability

This library module is available in the C-callable interface assembly formats. This library module is targeted for 56800E platforms.

3.7.5 Dependencies

List of all dependent files:

- 56800E_types.h
- 56800E_GFLIB library
- 56800E_MCLIB library
- ACLIB_TrackObsrvAsm.h
- aclib.h

3.7.6 Description

This function calculates the tracking observer algorithm where phase locked loop mechanism is adopted. It is recommended to call this function at every sampling period. It requires a single input argument as phase error. Such phase tracking observer, with standard PI controller used as the loop compensator, is depicted on Figure 3-9.

### Table 3-18. User type definitions

<table>
<thead>
<tr>
<th>Typedef</th>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f32Theta</td>
<td>in/out</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFFF</td>
<td>Estimated position as output of the second numerical integrator</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f32Speed</td>
<td>in/out</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFFF</td>
<td>Estimated speed as output of the first numerical integrator</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f32I_1</td>
<td>in/out</td>
<td>SF32</td>
<td>0x80000000...0x7FFFFFFF</td>
<td>State variable in controller part of the observer; integral part at step k-1</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f16PropScale</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer proportional gain</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>i16PropShift</td>
<td>in</td>
<td>SI16</td>
<td>-F..F</td>
<td>Observer proportional gain shift</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f16IntegScale</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Observer integral gain</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>i16IntegShift</td>
<td>in</td>
<td>SI16</td>
<td>-F..F</td>
<td>Observer integral gain shift</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>f16ThScaled</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>Scaling coefficient for output integrator of position</td>
</tr>
<tr>
<td>ACLIB_TRACK_OBSRV_T</td>
<td>i16ThShift</td>
<td>in</td>
<td>SI16</td>
<td>-F..F</td>
<td>Scaling coefficient shift for output integrator of position</td>
</tr>
</tbody>
</table>
Figure 3-9. Block diagram of proposed PLL scheme for position estimation

Depicted tracking observer structure has the transfer function as

\[
\frac{\hat{\theta}(s)}{\theta(s)} = \frac{sK_p + K_i}{s^2 + sK_p + K_i}
\]

\textit{Eqn. 3-57}

where the controller gains \(K_p\) and \(K_i\) are calculated by comparing the characteristic polynomial of the resulting transfer function to a standard second order system polynomial.

The essential equations for implementation of the tracking observer, according to block scheme in Figure 3-9, are as follows:

\[
\omega(k) = K_p \cdot e(k) + \Delta T_s \cdot K_i \cdot e(k) + I(k - 1)
\]

\textit{Eqn. 3-58}

\[
I(k) = \Delta T_s \cdot K_i \cdot e(k) + I(k - 1)
\]

\textit{Eqn. 3-59}

In equations \textit{Equation 3-58} and \textit{Equation 3-59}, there are coefficients and quantities that might be greater than one (for example, the actual rotor speed \(\omega(k)\)) or that are too small to be precisely represented within 16-bit fractional value. Due to this fact a special transformation have to be carried out in order to be successfully implemented using fractional arithmetic.

\[
K_p_{FRAC} = \frac{K_p}{\Omega_{MAX}}
\]

\textit{Eqn. 3-60}

\[
K_i_{FRAC} = \Delta T_s \cdot \frac{K_i}{\Omega_{MAX}}
\]

\textit{Eqn. 3-61}

\[
T_h_{FRAC} = \Delta T_s \cdot \frac{\Theta_{MAX}}{\Theta_{MAX}}
\]

\textit{Eqn. 3-62}

where the variables of the angle tracking observer are

- \(e(k)\) is observer error in step \(k\),
- \(\Delta T_s\) is the sampling period [s],
- \(\omega(k)\) is the actual rotor speed [rad/s] in step \(k\),
- \(\theta(k)\) is the actual rotor angle [rad] in step \(k\).

The scaled coefficients which are suitable for implementation on the DSP core are as follows:
3.7.7 Returns

The function returns an estimation of the actual rotor angle as 16 bit fractional value.

3.7.8 Range Issues

The function works with the 16-bit signed fractional values in the range <-1,1>.

3.7.9 Special Issues

The ACLIB_TrackObsrv function requires the saturation mode to be turned on. Upon completion of the function the saturation mode is set off.

3.7.10 Implementation

Example 3-6. Implementation Code

```c
#include "aclib.h"

ACLIB_TRACK_OBSRV_T acTo;
Frac16 f16ThetaError;
Frac16 f16PositionEstim;

void main (void)
{
    acTo.f32Theta = FRAC32(0.0);
    acTo.f32Speed = FRAC32(0.0);
    acTo.f32I_1 = FRAC32(0.0);
    acTo.f16PropScale = TRACKOBSRV_PROP_GAIN_SCALED;
    acTo.i16PropShift = TRACKOBSRV_PROP_GAIN_SHIFT;
    acTo.f16IntegScale = TRACKOBSRV_INTEG_GAIN_SCALED;
    acTo.i16IntegShift = TRACKOBSRV_INTEG_GAIN_SHIFT;
    acTo.f16ThScaled = TRACKOBSRV_TH_SCALED;
    acTo.i16ThShift = TRACKOBSRV_TH_SHIFT;
}

/* Periodical function or interrupt */
void ISR(void)
{
    f16PositionEstim = ACLIB_TrackObsrv(f16ThetaError, &acTo);
}
```

\[ f_{16KPScaled} = K_{pFRAC} \cdot 2^{-i16KPShift} \]  \hspace{1cm} \textit{Eqn. 3-63}  \\
\[ f_{16KIcaled} = K_{iFRAC} \cdot 2^{-i16KIShift} \]  \hspace{1cm} \textit{Eqn. 3-64}  \\
\[ f_{16ThScaled} = T_{hFRAC} \cdot 2^{-i16ThShift} \]  \hspace{1cm} \textit{Eqn. 3-65}
### 3.7.11 See Also

### 3.7.12 Performance

<table>
<thead>
<tr>
<th></th>
<th>Code Size (words)</th>
<th>Data Size (words)</th>
<th>Execution Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>0</td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>73/66 cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>73/66 cycles</td>
</tr>
</tbody>
</table>

Table 3-19. Performance of `ACLIB_TrackObsrv` function
3.8 ACLIB_Integrator

The function calculates the algorithm of numerical integrator of its input.

3.8.1 Synopsis

```c
#include "aclib.h"
Frac16 ACLIB_Integrator(Frac16 f16Xinp, ACLIB_INTEGRATOR_T *pudtIntg)
```

3.8.2 Prototype

```c
asm Frac16 ACLIB_IntegratorFAsm(Frac16 f16Xinp, ACLIB_INTEGRATOR_T *pudtIntg)
```

3.8.3 Arguments

<table>
<thead>
<tr>
<th>Name</th>
<th>In/Out</th>
<th>Format</th>
<th>Valid Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f16Xinp</td>
<td>in</td>
<td>SF16</td>
<td>$8000...$7FFF</td>
<td>input variable to be integrated</td>
</tr>
<tr>
<td>*pudtIntg</td>
<td>in/out</td>
<td>ACLIB_INTEGRATOR_T</td>
<td>N/A</td>
<td>pointer to structure which contain parameters of numerical integrator</td>
</tr>
</tbody>
</table>

3.8.4 Availability

This library module is available in the C-callable interface assembly formats.

This library module is targeted for DSC 56800E platforms.

3.8.5 Dependencies

List of all dependent files:
- 56800E_types.h
- 56800E_MCLIB library
3.8.6 Description

Numerical integration is the approximate computation of an integral using numerical techniques. The integrator is approximated by the backward Euler method, also known as backward rectangular or right-hand approximation as follows.

\[ I(k) = \Delta T_S \cdot in(k) + I(k - 1) \]

Eqn. 3-66

where the variables of the angle tracking observer are

- \( in(k) \) is integrator input in step \( k \),
- \( \Delta T_S \) is the sampling period [s],
- \( I(k) \) is the integrator value in step \( k \).

The integrator coefficient might be greater than one or that is too small to be precisely represented within 16-bit fractional value. Due to this fact a special transformation have to be carried out in order to be successfully implemented using fractional arithmetic.

\[ I_{FRAC} = \Delta T_S \cdot \frac{IN_{MAX}}{OUT_{MAX}} \]

Eqn. 3-67

The scaled coefficient which is suitable for implementation on the DSP core is follows:

\[ f16IScaled = I_{FRAC} \cdot 2^{-i16IShift} \]

Eqn. 3-68

3.8.7 Returns

3.8.8 The integrated value. Range Issues

The function works with the 16-bit signed fractional values in the range \(-1,1\).

3.8.9 Special Issues

The ACLIB_Integrator function requires the saturation mode to be turned on if the output variable is required to be limited otherwise output variable is naturally wrapped around.
3.8.10 Returns

The function returns an integrated value of its input variable.

3.8.11 Implementation

Example 3-7. Implementation Code

```c
#include "aclib.h"

ACLIB_INTEGRATOR_T acIntegrator;
Frac16 f16X;
Frac16 f16Intg;

void main (void)
{
    acIntegrator.f32I_1 = FRAC32(0.0);
    acIntegrator.f16IntegScaled = INTEG_GAIN_SCALED;
    acIntegrator.i16IntegShift = INTEG_GAIN_SHIFT;
}

/* Periodical function or interrupt */
void ISR(void)
{
    f16Intg = ACLIB_Integrator(f16X, &acIntegrator);
}
```

3.8.12 Performance

Table 3-22. Performance of ACLIB_Integrator function

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Code Size (words)</strong></td>
<td>18</td>
</tr>
<tr>
<td><strong>Data Size (words)</strong></td>
<td>0</td>
</tr>
<tr>
<td><strong>Execution Clock</strong></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>35/33 cycles</td>
</tr>
<tr>
<td>Max</td>
<td>35/33 cycles</td>
</tr>
</tbody>
</table>
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