University of Southern California

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# Matlab-based Software for Nonlinear Input-Output Modeling of Biomedical Systems

# LYSIS 7.2

## Biomedical Simulations Resource (BMSR)

by

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# User's Guide

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LYSIS User's Guide
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# ***Input-Output Modeling: Kernel estimation with Laguerre Expansions***

1. **LET_1**: Matlab function that estimates first-order and/or second-order kernels using the Laguerre expansion technique (LET) for a ***single-input/single-output*** system.

**function [Cest, Kest, Pred, NMSE] = LET_1(x, y, alpha, L, Q, Nfig);**

- ***Input variables***:
  1) ***x***: input-data vector
  2) ***y***: output-data vector
  3) ***alpha***: alpha parameter of Laguerre functions (from 0 to 1, default value: 0.5)
  4) ***L***: number of Laguerre functions used (from 1 to 9, default value: 5)
  5) ***Q***: order of the model : 1 for first-order or 2 for second-order (default value: 2)
  6) **Nfig**: an integer value for the first plotting window

- ***Output variables***:
  1) ***Cest:*** Laguerre coefficient estimates (structure array)
     a. Cest.c0 : constant
     b. Cest.c1 : first-order Laguerre coefficient estimates
     c. Cest.c2 : second-order Laguerre coefficient estimates
  2) ***Kest***: kernel estimates (structure array)
     a. Kest.k0 : constant
     b. Kest.k1 : first-order kernel estimate
     c. Kest.k2 : second-order kernel estimate
  3) ***Pred***: model prediction using the kernel estimates
  4) ***NMSE***: Normalized Mean-Square Error of model prediction

**How to run this program and what to expect**:

1. Input vector, "*x*", and output vector, "*y*", could be either row or column vectors whose lengths are equal. The code does not run when their lengths are different.

2. The value of Laguerre parameter "alpha" should be between 0 and 1 (default value = 0.5). Alpha value is selected by user after searching for minimum NMSE of model prediction.
3. The number of Laguerre functions "*L*" used in LET should be between 1 and 9 (default value = 5). *L* is selected by user after searching for minimum NMSE of model prediction.
4. The model order "*Q*" should be either 1 (first-order) or 2 (second-order) (default is 2).
5. "Nfig" is the first plotting window number that display the kernel kernel estimates; the model prediction, the actual output and the residuals are displayed in window (Nfig+1).

** Example of running **LET_1** when alpha = 0.3; L = 5; Q = 2; Nfig = 1:*

**[Cest, Kest, Pred, NMSE] = LET_1(x, y, 0.3, 5, 2, 1);**

After running the code, plotting window (Nfig) displays the first-order and the second-order kernel estimates (when *Q* = 2), and window (Nfig+1) displays the model prediction (in red, top panel), the output signal (in blue, top panel) and the error between the actual output and the model prediction (bottom panel) along with the NMSE value. Note that "***Cest***" and "***Kest***" are both structure arrays. The variable "***Pred***" is the model prediction with length equal to the output vector.

***You can test this code by running the program: test_LET1 in the LYSIS 7.2 directory.***

**2.** **LET_2**: Matlab function that estimates first-order and second-order kernels using the Laguerre expansion technique (LET) for ***dual-input/single-output*** system.

**function [Cest, Kest, Pred, MNSE] = LET_2(x1, x2, y, alpha1, alpha2, L1, L2, Q, Nfig);**

- ***Input variables***:
  1) ***x*1**: first input-data vector
  2) ***x*2**: second input-data vector
  3) ***y*:** output-data vector

4) ***alpha1***: parameter alpha of Laguerre functions for $x1$ (default value: 0.5)
5) ***alpha2***: parameter alpha of Laguerre functions for $x2$ (default value: 0.5)
6) ***L1***: number of Laguerre functions for $x1$ (default value: 5)
7) ***L2***: number of Laguerre functions for $x2$ (default value: 5)
8) ***Q***: order of the model ($Q$ = 1 or 2, default value: 2)
9) **Nfig**: an integer value for the first plotting window

- ***Output variables***:
  1) ***Cest***: Laguerre coefficient estimates (structure array)
     a. ***Cest.c0*** : constant
     b. ***Cest.c10*** : Laguerre coefficient estimates of first-order kernel for $x1$: *k10*
     c. ***Cest.c20*** : Laguerre coefficient estimates of second-order kernel for $x1$: *k20*
     d. ***Cest.c01*** : Laguerre coefficient estimates of first-order kernel for $x2$ : *k01*
     e. ***Cest.c02*** : Laguerre coefficient estimates of second-order kernel for $x2$ : *k02*
     f. ***Cest.c11*** : Laguerre coefficient estimates of second-order cross-kernel : *k11*
  2) ***Kest***: kernel estimates (structure array)
     a. ***Kest.k0*** : constant
     b. ***Kest.k10*** : first-order kernel estimate for $x1$
     c. ***Kest.k20*** : second-order kernel estimates for $x1$
     d. ***Kest.k01*** : first-order kernel estimate for $x2$
     e. ***Kest.k02*** : second-order kernel estimates for $x2$
     f. ***Kest.k11*** : second-order cross-kernel estimate between $x1$ and $x2$
  g. ***Pred***: model prediction
  h. ***NMSE***: Normalized Mean-Square Error of model prediction

**How to run this program and what to expect**:

1. Two input vectors, "$x1$" and "$x2$", and one output vector, "$y$", are either row or column vectors of equal lengths. The code does not run when their lengths are different.
2. Laguerre parameter values of "alpha1" (for first input, "$x1$") and "alpha2" (for second input, "$x2$") should be between 0 and 1 (default value = 0.5). Alpha values are selected by the user after searching for minimum NMSE of model prediction.

3. Values of "*L*1" and "*L*2" should be between 1 and 9 (default value = 5). *L*1 and *L*2 values are selected by user after searching for minimum NMSE of model prediction.
4. Model order "*Q*" should be either 1 (first-order) or 2 (second-order). Default: *Q* = 2.
5. "Nfig" is the first window number that displays the kernel estimates for *x1*, while the kernel estimates for *x2* are displayed in window (Nfig+1), the cross-kernel estimate in window (Nfig+2), and the model prediction and residuals in window (Nfig+3).

* *Example of running **LET_2** for: alpha1=0.3, alpha2=0.5, L1=5, L2=3, Nfig=1:*

**[Cest, Kest, Pred, NMSE] = LET_2(x1, x2, 0.3, 0.5; 5, 3, 2, 1);**

After running the code, plotting windows (Nfig) and (Nfig+1) display the first-order and the second-order kernel estimates (when *Q* = 2) for the first and second inputs, respectively, window (Nfig+2) displays the second-order cross-kernel (when *Q* = 2), and window (Nfig+3) displays the model prediction (in red, top panel), the output signal (in blue, top panel), and the error between the output signal and the model prediction (bottom panel) along with the NMSE value of the model prediction. Note that "***Cest***" and "***Kest***" are both structure arrays. The variable "***Pred***" is the model prediction with length equal to the output vector.

***You can test this code by running the program: test_LET2 in the LYSIS 7.2 directory.***

# ***PDM-based Nonlinear Input-Output Modeling***

1. **PDM_1**: Matlab function that computes the "***Principal Dynamic Modes***" (PDMs) of a system using the first-order and second-order kernel estimates that are obtained via the Laguerre expansion technique (LET) for a ***single-input/single-output*** system. It also estimates the "***Associated Nonlinear Function***" (ANF) for each computed PDM.

**function [Npdms, PDMs, ANFs, Pred, NMSE] = PDM_1(x, y, alpha, L, Nfig)**

- ***Input variables***:
  1) ***x***: input-data vector
  2) ***y***: output-data vector
  3) ***alpha***: alpha value of Laguerre functions (default value: 0.5)
  4) ***L***: number of Laguerre functions (default value: 5)
  5) ***Nfig***: an integer value for plotting windows

- ***Output variables***:
  1) ***Npdms***: number of PDMs
  2) ***PDMs***: estimates of Principal Dynamic Modes
  3) ***ANFs***: cubic polynomial function (with zero constant term) for each PDM
     a. ANFs.const - constant term of ANFs
     b. ANFs.pdmX - ANFs for PDM #X (first, second, and third order coefficients)
  4) ***Pred***: PDM-based model prediction
  5) ***NMSE***: normalized mean-square error of PDM-based model prediction

**How to run and what to expect**:

1. Input vector, "*x*", and output vector, "*y*", could be either row or column vectors whose lengths are equal. The code does not run when their lengths are different.
2. Value of "alpha" should be between 0 and 1 (default value = 0.5). Alpha value is selected by user after searching various values for minimum NMSE.

3. Value of "*L*" should be between 1 and 9 (default value = 5). *L* value is selected by user after searching various values for minimum NMSE.
4. "Nfig" is the first plotting window number that displays the kernel estimates; (Nfig+1) window displays the singular values and their cumulative sums; (Nfig+2) window displays the PDMs; (Nfig+3) window displays the cubic ANFs; (Nfig+4) window displays the model prediction and residuals.

* *Example of running* **PDM_1** *when alpha = 0.5; L = 5; Nfig = 1:*

**[Npdms, PDMs, ANFs, Pred, NMSE] = PDM_1(*x*, *y*, 0.5, 5, 1);**

After running the code, the plotting window (Nfig) displays the first and second order kernel estimates; window (Nfig+1) shows the singular values and their cumulative sums; and Matlab command-space asks how many PDMs (between 1 and *L*) should be computed. When a positive integer value of "Npdms" is entered, window (Nfig+2) shows the PDMs in the time domain and window (Nfig+3) shows the cubic ANFs for these PDMs. Window (Nfig+4) shows the model prediction (in red, top panel), the output signal (in blue, top panel) and the error between the output signal and the model prediction (bottom panel) along with normalized mean-square error (NMSE) value.
The first output variable "Npdms" is the selected number of PDMs; the second variable "PDMs" are the PDMs estimates and the third variable "ANFs" has the coefficients (of first, second and third degree) of the ANFs for the respective PDMs and a constant. NOTE: the "PDMs" and "ANFs" are structure array. "Pred" is the model prediction whose length is the same as the output vector, and the corresponding NMSE value.

***You can test this code by running the program: test_PDM1 in the LYSIS 7.2 directory using data from test_LET1 .***

**2.** **PDM_2**: Matlab function that computes the "***Principal Dynamic Modes***" (PDMs) of a system using the first-order and second-order kernel estimates that are obtained via the

Laguerre expansion technique (LET) for a ***two-input/single-output*** system. It also estimates the "***Associated Nonlinear Function***" (ANF) for each computed PDM and the ***cross-terms***.

**function [Npdms1, PDMs1, Npdms2, PDMs2, ANFs, Pred, NMSE] =**
**PDM_2(x1, x2, y, alpha1, alpha2, L1, L2, Nfig)**

- ***Input variables***:
  1) ***x1***: first input-data vector
  2) ***x2***: second input-data vector
  3) ***y***: output-data vector
  4) ***alpha1***: parameter of Laguerre functions for the first input (default value: 0.5)
  5) ***alpha2***: parameter of Laguerre functions for the second input (default value: 0.5)
  6) ***L1***: number of Laguerre functions for the first input (default value: 5)
  7) ***L2***: number of Laguerre functions for the second input (default value: 5)
  8) ***Nfig***: an integer for the first plotting window

- ***Output variables***:
  1) ***Npdms1***: number of PDMs for the first input
  2) ***PDMs1***: PDM estimates for the first input
  3) ***Npdms2***: number of PDMs for the second input
  4) ***PDMs2***: PDM estimates for the second input
  5) ***ANFs***: cubic polynomials for each PDM estimate (structure array)
     a. ANFs.const: constant term of PDM-based model
     b. ANF.iXpdmY : cubic ANF coefficients for input X and PDM Y (zero constant)
     c. ANFs.cross_terms: coefficients of the significant cross-terms, which are pair-products of PDM-outputs selected for statistical significance by use of the w-statistic
  6) ***Pred***: PDM-based model prediction
  7) ***NMSE***: normalized mean-square error of PDM-based model prediction

**How to run and what to expect**:

1. Two input-data vectors, "*x*1" and "*x*2", and one output-data vector, "*y*", are either row or column vectors with equal lengths. The code does not run when their lengths are different.
2. Values of "a1" (for first input, "*x*1") and "a2" (for second input, "*x*2") should be between 0 and 1 (default value = 0.5) and they are selected by the user for minimum NMSE.
3. Values of "*L*1" and "*L*2" should be between 1 and 9 (default value = 5). *L*1 and *L*2 values are selected by user after searching various values for minimum NMSE.
4. "Nfig" is the first plotting window number to display two results: kernel estimates in Nfig and Nfig+1 windows for the first and second inputs, respectively; and cross-kernel estimate in Nfig+2 window (when *Q* = 2); and model prediction in Nfig+3 window.

* *Example of running **PDM_2** when a1 = 0.3; a2= 0.5; L1 = 5; L2 = 3; Nfig = 1*:

**[Npdms1, PDMs1, Npdms2, PDMs2, ANFs, Pred, NMSE] = PDM_2(*x*1, *x*2, *y*, 0.3, 0.5, 5, 3, 1);**

After running the code, window (Nfig) displays the singular values and their cumulative sums for the first input, and Matlab command-space asks for a number of PDMs (≤ *L*1) for the first input. Then window (Nfig+1) displays the first-input PDMs in time domain. The same sequence of displays takes place on windows (Nfig+2) and (Nfig+3) for the second input. Windows (Nfig+4) and (Nfig+5) show the estimated cubic ANFs for the first-input and second-input PDMs, respectively. Window (Nfig+6) shows the model prediction (in red, top panel), the output signal (in blue, top panel) and the error between the output signal and the model prediction (bottom panel) along with the resulting NMSE. "Npdm1" is the number of first-input PDMs. "PDMs1" is the first-input PDM estimates. "Npdms2" is the number of second-input PDMs. "PDMs2" is the second-input PDMs estimates. "ANFs" (a structure array) contains the coefficients of the cubic Associated Nonlinear Function for each PDM and the selected significant cross-terms, as well as a constant term. "Pred" is the model prediction with length equal to the output-data vector.

***You can test this code by running the program: test_PDM2 in the LYSIS 7.2 directory using data from test_LET2.***