Identification of the Electro-Hydraulic Actuation System Dynamics

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***Abstract* - System Identification plays a significant role in design and development of an Electro-Hydraulic Actuation System (EHAS) for a developmental aero-engine. System Identification is a process for determining a mathematical model of dynamic system experimentally. In practical applications, the most effective use of system models in control design are based on frequency domain transfer functions. System Identification of a typical EHAS has been carried out utilizing OPAL-RT based multi-domain Modeling and Simulation framework. The experimentally obtained EHAS model has been validated with the empirical model and results are found to be satisfactory covering both steady state and transient behavior.**

***Index Terms*- EHAS, EHSV, OPAL-RT, LVDT, MATLAB, CVGAS**

I. INTRODUCTION

System Identification, the first step in the model-based control design is a process of building mathematical models of a dynamic system experimentally to understand and predict its behavior. System Identification deals with data processing techniques that includes design of experiment – to make choices so that the data become maximally informative, mathematical model structure selection, numerical methods of parameter estimation and also statistical techniques in interpreting results. A frequency domain approach is followed to experimentally obtain the mathematical model of a typical EHAS of a developmental aero-engine. The experimentally generated EHAS model is further validated with the empirical model referred in [1]. Finally the results are found to be satisfactory.

II. THEORETICAL BACKGROUND

A linear system is uniquely determined by its impulse response or its frequency response $G(i\omega)$ (the Laplace transform of impulse response evaluated at $s=i\omega$). While the transient and correlation analysis aims at different estimates of the impulse response and there are several techniques to directly estimate the frequency response. The frequency-response analysis through correlation method is proposed which is less sensitive to noise and very much useful under practical circumstances [2][3]. As per [3], consider a linear time invariant system with transfer function $G(s)$ indicated in Fig.1.

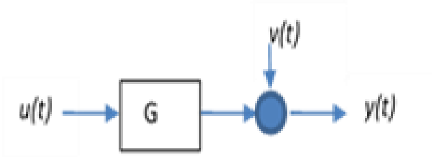

Fig.1 A linear Time Invariant System with disturbance

For a given input $u(t) = u_o \cos \omega t$

The system output is

$y(t) = y_o \cos (\omega t+\phi) + v(t) + transients$

where $v(t)$ is the noise and once the possible transients have faded away, the output signal is $y(t) = y_o \cos (\omega t+\phi)$

Where magnitude, $y_o = |G(e^{i\omega})| . u_o$, & ϕ = arg $G(e^{i\omega})$ radians.

When the input $u(t)$ is a sinusoid, the steady state output is a sinusoid of the same frequency of $u(t)$, but multiplied in magnitude by $|G(e^{i\omega})|$ and shifted in phase by ϕ. If the system is driven by the input for a certain u_o, ω_1 and when we measure y_o and ϕ from the output signal, it is possible to determine the complex number $G(e^{i\omega 1})$. Repeating this procedure for a number of different ω in the interested frequency band, we get a good estimate of the function $G(e^{i\omega})$. In frequency response analysis, it is difficult to determine the ϕ directly due to the presence noise and irregularities. A good approach to eliminate the noise is correlation analysis and since the component of $y(t)$ is of interest and is a cosine function of known frequency, it is possible to correlate $y(t)$ out from the noise $v(t)$.

III. EXPERIMENTAL SET-UP FOR SYSTEM IDENTIFICATION

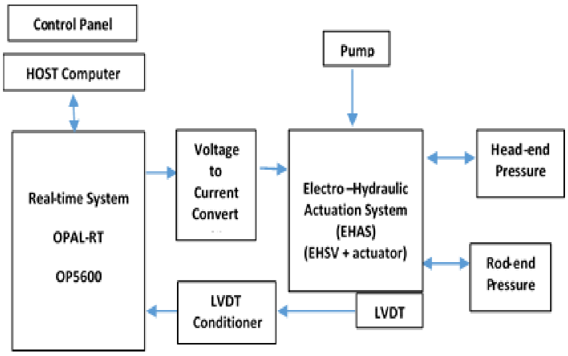

Fig.2 System Identification set-up for EHAS

OP5600	• A real-time computer
OP5340 Analog Input Module	• 6 differential analog input channels • One 16 bit ADC/channel and Simultaneous sampling on all channels • Maximum of 500k/s update rate per channel with throughput of 8 MS/s • Programmable ranges from +/- 100mV to +/- 20V
OP5330 Analog Output Module	• 6 analog output channels • Simultaneous output on all channels with 1MS/s max. update rate • Programmable ranges from +/- 100mV to +/- 17V • Outputs short-circuit protected
Voltage to Current Converter Module (VC2124)	• Two channels of voltage to current conversion • Input voltage range +/-10V. • A switch selectable full scale output current from +/-10mA to +/- 100mA. Full scale output current is selected from -20mA to +20mA. • Powered by single 24V power supply
LVDT Signal Conditioner (Model No. LVDT-DBV)	• Input type: 5 wire LVDT • Excitation voltage: 5.3Vrms • Excitation Frequency: 2000Hz • Output: +/- 10Vdc • Supply: 24Vdc, 125mA

Table I Hardware Configuration

The OPAL-RT© based experimental set-up for carrying out the system identification of a typical EHAS is indicated in Fig.2 and table I indicates the hardware configuration of the framework. The OPAL-RT© OP5600 is the real-time computer where the dynamic simulation models are executed with 1msec time step. It comprises a target computer, a high-speed front end processor and a signal conditioning stage. Target computer communicates with other subsystems through the I/O cards installed in it. The simulator converts the software generated signals into real world signals. The front of the chassis provides the monitoring interfaces and access to all I/O connectors, power cable and main power switch is provided at the back of the chassis. In the current test analog input channel of analog I/O card is used to receive LVDT feedback signal and analog output channel is used to provide drive signal for EHSV.

IV. EXPERIMENTAL DESIGN

The work proposed is to obtain a mathematical model of a Compressor Variable Geometry Actuation System (CVGAS), a typical EHAS of a developmental aero-engine. The model is generated based on best-fit criteria, residual analysis of auto-correlation and cross-correlation between the input and output signals. The 3dB point (bandwidth) of the actuator control is expected to be at 3Hz. Generally EHSVs are modeled by simple lag systems, which are sufficient for control system design. Hence servo valve current to actuator velocity transfer function can be taken as first order lag with transport delay. Actuator position is measured from LVDT and recorded during test. Since in the existing setup there is no provision to directly measure actuator velocity, it can be obtained by differentiating actuator position. However in this study linear transfer function identification is carried out between input current and output EHAS actuator position, as the spikes in actual position data can make the velocity data noisy after differentiation. Low pass filtering is done on the raw input and output data to remove high frequency noise. We are usually interested in open loop models of a physical system in the system identification process. Most dynamic systems operate in closed loop and in this activity frequency response test was carried out in closed loop with sinusoidal input frequency sweep from 0.1 Hz to 4Hz. Experimental data obtained from frequency response test is used for system identification. The phase shift and gain between input and output are calculated at different frequencies and bode of the assumed model is fitted to the experimentally obtain phase shifts and gains.

V. PROCEDURE TO CALCULATE THE GAIN AND PHASE SHIFT

The below procedure calculates the gain and phase shift at one frequency within the desired the range of 0.1Hz to 4Hz. Similar process is followed at other frequencies also to obtain gain and phase.

Step 1: Input -EHAS drive current and output - EHAS actuator position is read from recorded .mat file. The input (drive current, mA) and the output (actuator position, mm) data is plotted in Fig.3, which shows data for frequency range from 0.1 Hz to 4 Hz. However frequencies up to 2Hz are taken for identification since at the remaining frequencies, the saturation in current input invalidates the data.

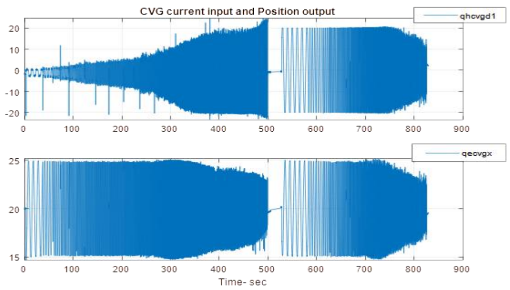

Fig.3 Data file

Step 2: The low pass filtering is performed on the data read in step 1. Filter is designed using MATLAB® functions 'designfilt' and 'filtfilt' with filter characteristics mentioned below

Type – low pass filter
Pass band Frequency - 12 Hz
Stop band Frequency- 12 Hz
Pass band Ripple - 0.001
Stop band Attenuation - 60 dB
Sample Rate - 50 Hz

Step3: Input and output signal corresponding to 2Hz frequency is extracted to calculate gain and phase difference between input and output at 2Hz frequency as shown in Fig.4. The procedure to calculate gain and phase difference between input and output signals at other test frequencies will be similar.

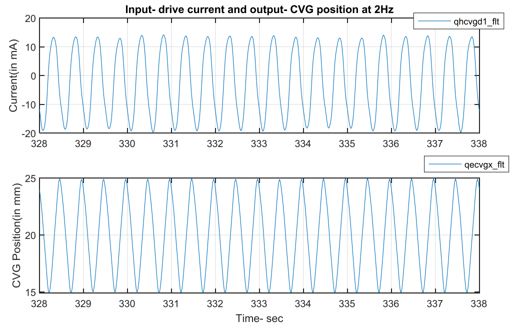

Fig.4 Input drive current and actuator position

Step 4: Input offset and output offset is removed from the sliced signals as shown in Fig.5.

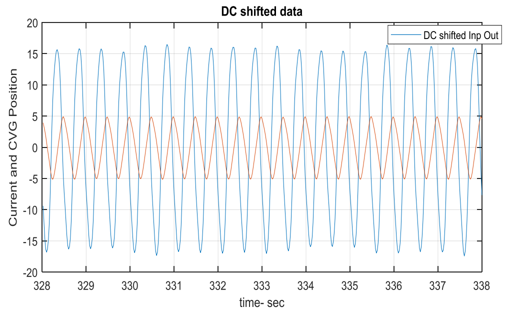

Fig.5 Input and output signals (Offset removed)

Step 5: The gain (output magnitude/input magnitude) and phase difference are calculated between processed input and output signals obtained in previous step.

Calculation of Phase:

- For phase (lead/lag) calculation, *correlation* between input and output signal is obtained and the point at which maximum correlation between input and output is obtained, is extracted, (i.e time shift of input signal with respect to output signal).
- This time shift of one signal with respect to other corresponding to maximum correlation is used to calculate phase shift.
- Phase shift = time shift*peak frequency*360

Calculation of Gain:

- To calculate gain, shifted output signal is subtracted from assumed gain multiplied with input signal and the error is minimized iteratively.
- The gain at which this error is minimum is assumed as the system gain at given test frequency.
- Phase difference and gain is calculated for other test frequencies also by the same process.

All the plots indicate EHAS response for 2Hz input signal. Fig.6 shows phase corrected signals and Fig.7 shows phase and gain corrected signals, Fig.8 indicate the error versus system gain and correlation between the input and output, Fig.9 indicates cross-correlation between input current and output position signals and Fig.10 shows the FFT of the 2Hz input signal.

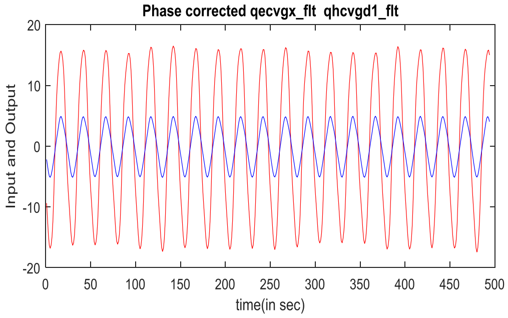

Fig.6 Phase corrected signal

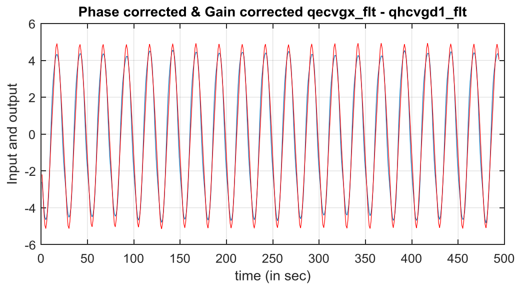

Fig.7 Gain & Phase corrected Signals

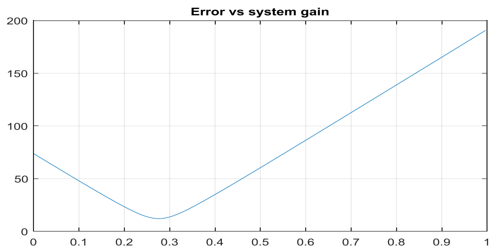

Fig.8 Error Vs Gain plot at 2Hz frequency

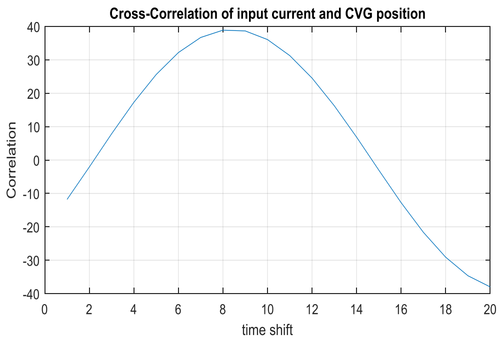

Fig.9 Cross –correlation of Input and Output signal

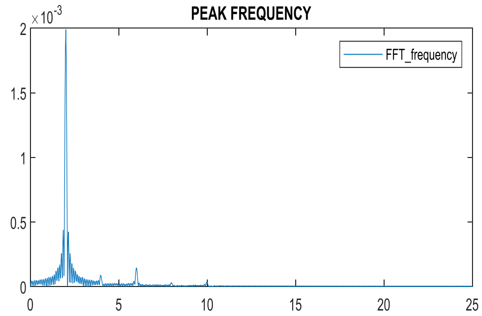

Fig.10 FFT of 2Hz input signal

Peak Frequency	Gain	Phase, degrees
0.1	2.5	85.0
0.3	1.7	90.7
0.5	1.25	95.9
1.0	0.7	108.1
1.4	0.45	110.2
1.8	0.32	117.0
2.0	0.28	120.3

Table II Gain and Phase difference at different frequencies

The EHSV drive current to EHAS velocity linear transfer function is taken as first order lag with delay. The actuator position is obtained by integrating velocity with a transport delay of T. Thus servo current to CVG position transfer function becomes second order and is given by-

$$\text{sys}=\frac{k}{s(\tau s+1)}e^{-Ts}$$

Using 'bode' function gain and phase of the assumed second order system with initial guesses of K, τ and T at given test frequencies are obtained and error norm is calculated by subtracting these gain and phase values from the calculated phase and gain values from the experimental data in the previous step. The error norm is minimized iteratively using 'fmincon' MATLAB® function. The optimized unknown parameters K, τ and T are obtained at the minimum error norm.

The MATLAB® Function 'fmincon' finds minimum of constrained non-linear multi-variable function inputs:

– Function to minimize. (fun)
– Initial guess. (x0)
– Constraint matrices. (A, b, Aeq, beq)
– Upper and lower bounds for the solution. (xlb, xub)

VI. VALIDATION OF EHAS MODEL USING MATLAB CONTROL SYSTEM TOOL BOX

Step1: Data import- Calculated the magnitude and phase difference between input signal (Drive current) and output signal (MMV position) for different frequencies. The frequency response data is then stored in an idfrd object and imported into System identification toolbox for system identification as indicated in Fig.11.

MATLAB code:

```
W =[0.1   0.3 0.5 1.0 1.4 1.8]*2*pi; % Frequency in rad/sec
AMP = [2.5 1.7   1.25   0.7 0.45 0.32 0.28]; % Amplitude
PHA = [-85.0 -90.7 -95.9 -108.1 -110.2 -117.0 -120.3]; % Phase difference
zfr = AMP.*exp(1i*PHA*pi/180);
Ts = 0.001;
gfr = idfrd(zfr,W,Ts);     % stored in idfrd object
```

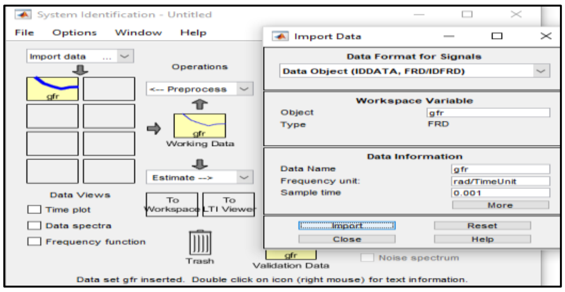

Fig.11 MATLAB Control System tool Box

Step 2: System identification estimation using process models feature in system identification toolbox as shown in Fig.12 and iterative minimization as indicated in Fig.13.

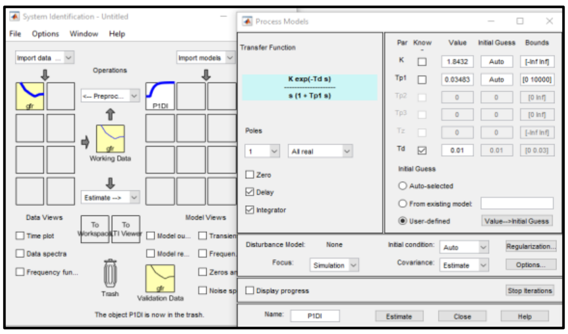

Fig.12 Estimation process

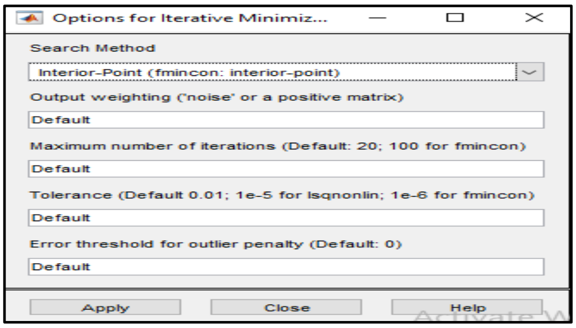

Fig.13 Iterative Minimization Process

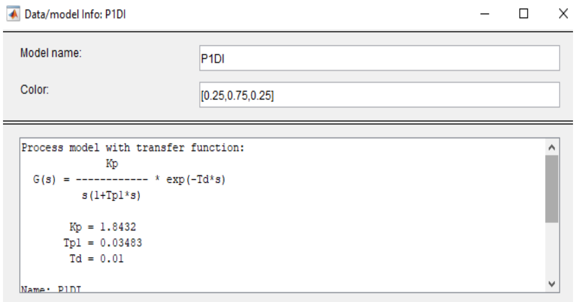

Fig.14 Transfer function Model (MATLAB Toolbox)

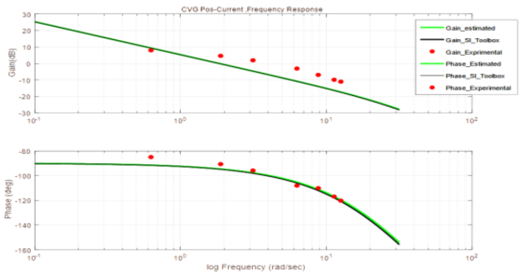

Fig.15 Bode plots of Estimated, SI toolbox generated model and Experimental EHAS model

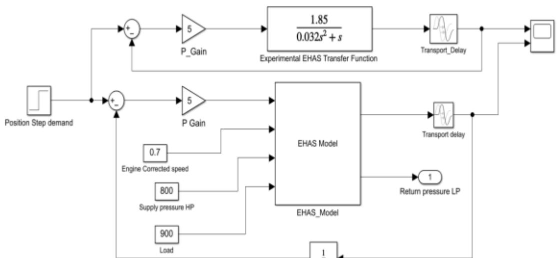

Fig.16 Validation of experimental EHAS model with empirical EHAS model

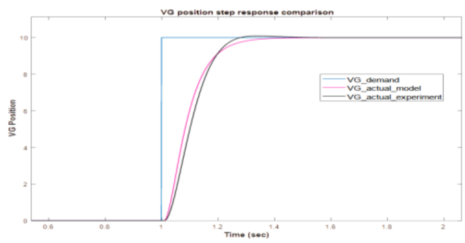

Fig.17 Validation of Simulink EHAS Reduced Model with Experimentally generated EHAS model (Step Response)

Model Generation mode	EHAS Model
Empirical	State space EHAS Simulink model [3]
Experimental EHAS Model generated through customized MATLAB code	$\text{sys}=\frac{1.85}{s(0.032s+1)}e^{-0.01S}$
MATLAB Control Tool Box generated EHAS Model	$\text{sys}=\frac{1.8432}{s(0.03483s+1)}e^{-0.01S}$

Table III

ANALYSIS AND RESULTS

The experimental EHAS model obtained through correlation method is compared with EHAS model generated through MATLAB control system toolbox exhibiting best-fit criteria of 95.86%. The transfer function model is indicated in Fig.14 and bode plot in Fig.15. Further this model is validated with 4 state state-space empirical EHAS model in the M&S framework as shown in Fig.16 which exhibits satisfactory steady state and transient behaviour as indicated in Fig.17.

CONCLUSION

System identification of CVGAS, a typical EHAS was carried out using experimental data adopting frequency analysis through correlation method. Multi-sine signal input with frequency varied from 0.5Hz to 4 Hz used to cover the expected 3dB bandwidth of the system. A high speed real time controller with data recording feature was configured with the help of OPAL-RT real time computer as a part of Modeling & Simulation framework with 1msec sampling time. The same experimental set-up as a part M&S framework can be utilized in identifying the other EHASs of a developmental aero-engine.

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