Diagnostics of actuation system by Hadamard product of integrated motor current residuals applied to electro-mechanical actuators

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ABSTRACT

The paper presents diagnostics methodology that can identify the event of occurrence of fault in the actuator or the linkage system of the flight control actuation system driven by Linear Electromechanical Actuators (LEMA). The standard data analysis like motor current signature analysis (MCSA) is good at identifying the incipient faults within the elements of the actuators in situations where-in the actuators are driving control surfaces. But in back driven cases, where-in LEMA is driven back by control surfaces, the faults outside the LEMAs are difficult to be detected due to higher mechanical advantages of transmission elements like roller screws, gear train and linkage arms scaling down their effects before reaching the motor. One such event occurred in a ground test, wherein the jet vanes were sheared when back driven by excessive gas dynamic forces. Neither the motor current nor the LEMA position feedback data has any clue of the instance of occurrence of such shearing. The case study is discussed in detail and diagnostics solution for such failures is proposed. A new methodology to pin point the event of occurrence is arrived at based on ground static test data of four independent channels. The same is reassured for its applicability using lab experiments on three samples mimicking the failure. The method's applicability is also extended for extracting events in actual flight, by comparing the flight telemetry data with the mimicked lab level (dry runs) data. The methodology uses the analysis of LEMA motor current data to arrive at the vital diagnostic information. The current data of LEMA directly can't be interpreted due to non-stationary nature arising from variable speed and its pulsating form because of the pulse width modulation (PWM) switching, threshold voltages and closed loop dynamics of the servo. Hence the motor current is integrated using cumulative trapezoidal method. This integrated data is spline curve fitted to arrive at residuals vector. The Hadamard product is used on the residuals vector to amplify the information and suppress the noise. Further, normalizing is done to compare data across tests and samples. With this, necessary diagnostic information was extracted from static test data. The method is extended for extracting diagnostics information from actual flight using comparison analysis of, the test data in actual environment with mimicked lab level dry runs. It is also verified for applicability in faults directly driven by actuators in lab level experiments on three samples.

1. INTRODUCTION

Linear Electromechanical Actuators (LEMAs) are widely used in control actuation systems of flight vehicles. The present study is focused on the development of methodology to cater the diagnostic needs of faults in transmission elements of flight actuation systems driven by linear electro mechanical actuators. The study analyses test data of a thrust vectoring system and arrive at methodology of extracting diagnostic information. The method is further verified for its applicability for actual flight telemetry data. The same is also verified for its applicability in driving mode load conditions on three lab level tests. The TVC uses jet vanes, which are far off from the motor wherein loads transmitted are attenuated by mechanical advantages of linkage system and are also masked by closed loop dynamics of servo system posing difficulty in acquiring the diagnostic signatures.

In one of the six component static tests all the four Jet vanes of TVC system are sheared off due to excessive external gas dynamic loads. Surprisingly, no observable deviations are there in the data acquired from the LEMAs driving these jet vanes in terms of position commands, position feedbacks and motor currents. The ground instrumentation data of the static test stand was handy in arriving at the diagnostic information.

Efforts were made to make such information available from the existing actuator data as no additional data is possible in the actual flight tests. This paper presents the methodology of extracting diagnostic information of the mechanical elements of transmission mechanism far away from the driving actuator.

The system under study uses Linear Electromechanical Actuators (LEMA) for driving the aerodynamic control surfaces and thrust vectoring jet vanes simultaneously. The load capacity of LEMAs hence is huge as they are designed to meet the both loads. TVC loads are meager in the present system compared to aerodynamic loads. Hence, the load effects of jet vanes were contributing to minor portion of motor current changes. It posed difficulty in extracting diagnostic information from motor current data analysis. Even the complete shear of jet vane was not having any clue in LEMA current data. Such diagnostic information is vital for the post test analysis for ground as well as flight tests, a strong need was felt to arrive at methodology which can extract TVC systems diagnostic information based on LEMA motor current data. This is due to the fact that in actual flight data, LEMA data alone is available and no additional sensors are possible due to telemetry channels and bandwidth limitations.

Four LEMAs are used in control of flight vehicle to turn it in the required pitch, yaw and roll directions. Unlike electric motors which run in continuous rotation resulting in stationary data, reciprocal motion only will be possible in case of LEMAs. Diagnostics is difficult for such systems as they are running in continuously varying speed making standard spectral methods like Fast Fourier transform (FFT) not applicable and also the closed loop control masks the effects of faults till they become uncontrollable as explained by (Babu et al., 2011). Hence diagnostics of LEMAs is a research challenge.

Actuation systems with LEMAs will generally have higher reduction ratios from motor rotation to control surface deflections (in orders of 200-300) through mechanical transmission elements like bearings, gears, ball / roller screws and linkages. (Benbouzid, 2000) used induction motors current signatures as a medium of fault detection for motor electrical and mechanical faults. In driving mode, LEMA motor current information is useful in analyzing the condition of flight actuation system. Condition monitoring will pose difficulties in driven mode (aiding mode), where-in the LEMA is back driven by aerodynamic / gas dynamic loads. This is due to fact that, the load effects at the control surface / jet vane will be attenuated by transmission elements before reaching the motor. This is analogous to the screw jack effect, the motor driving screw jack feels the load dynamics while driving it up against weight, but in reverse, the motor is blind to load dynamics. The static test failure data analysis has open up additional difficulty in extracting diagnostic information in back driven mode. The motor current data analysis is better in detecting faults directly in motor, good in detecting faults in connected gear train, reasonable for faults in the transmission mechanisms like roller screws, difficult in accessing fault information in linkages and very difficult to identify health degradation which are further away like control surfaces. In addition, the failures are more probable at the farther ends due to higher torques and loads acting compared to the motor elements which operate at lower torques and loads, but at higher speeds. (Mohamed & Windelberg, 2017) explained difficulties and devised techniques for detection of faults in bearings of ball screw driven electro mechanical actuators. Hence, strong need of diagnostic methodology which can extract information in both aiding and opposing loads and also faults of all actuation system components from motor till control surface is addressed in present work.

1.1. Diagnostics of Flight Linear Electromechanical Actuators

The linear electromechanical actuators (LEMAs), are more popular in flight control actuation systems and are mission critical. (Wagner, 2011) discussed various challenges faced in health monitoring specific to electromechanical flight control actuation systems. Condition monitoring techniques using Vibration, Acoustics and motor current signals are popular. Motor Current Signature Analysis (MCSA) is most preferable technique for such systems as they are electric motor driven. Other techniques like vibration data needs additional sensors, more sampling rates and additional channels in telemetry.
Hence, there is a practical constraint on arriving at the diagnostic information from existing motor current data available in telemetry. Standard MCSA methods can detect failure in motor components. (Romeral et al., 2010) discussed various fault detection techniques by monitoring motor current. Motor current data of LEMA is highly pulsating due to pulse width modulation and closed loop dynamics, making it difficult to correlate with any physical parameter of motor unlike in induction motors. Most of the MCSA methods use frequency domain methods like FFT, STFT and Wavelets to arrive at the condition monitoring information. This paper uses completely time domain analysis, as the focus was on extracting event based information. This method is able to detect failures which are in elements far away from motor in the transmission chain (Jet vanes being the last element of TVC). Various methods were attempted and the successful one is presented in this paper.

1.2. The Case study

During static test (elaborated in Section 2), all the four jet vanes used in thrust vector control (TVC) were sheared off at the jet vane and shaft interface portion due to excessive gas dynamic load from nozzle exit Jet flames. The fact of shearing of all the four TVC jet vanes at about 4.7 seconds is ascertained by the side force data from the static test facility instrumentation, high speed video footage and post test visual observations of the hardware. The details of system in terms of its configuration and specifications are thoroughly discussed by (Bhaskar et al., 2015). Post test analysis was carried out and no clue of the shearing of the vanes is found in data acquired from all the four LEMAs (Position, Velocity & Current) channels. This was attributed to the mechanical advantage of the TVC actuation system (1:200). The load experienced by TVC system has attenuated while passing through the linkages, roller screw and the gear train before reaching the brushless direct current (BLDC) motor. Hence the current spike which can be attributed to such event is almost unidentifiable in the motor current data. Motor current data in the period of interest was similar to the current drawn at other instants with similar LEMA commands post failure. Motor current is expected to have evidence of the event because load is expected to drop at instant of shear as load drops to zero. The data has no observable information in the probable time gap arrived from the static test facility data analysis.

It is essential to extract such information from the LEMA data because, in actual flight there will be no access to post flight hardware. (Barnett et al., 2012) have devised a test setup for aircraft electromechanical actuation systems to mimic the flight loads on ground. A need is felt to devise a methodology to arrive at such information from the telemetry data of LEMAs. The paper presents the methodology devised from static test data and verified on three lab level tests.

The static test data has profiles which are repeated in time instances, making time series analysis convenient to model.
The steps involved in the method are, Integrating the current data, arriving at a mathematical curve fit, taking residuals of the fit, raising residuals to higher powers point wise using Hadamard product and normalise the outcome for cross comparison.

BLDC motor current is highly pulsative in nature Integrating the current data smoothened it and was able to give it physical meaning of energy consumed by motor till that instant (Battery discharge). A mathematical spline fit for the data is done. From the model fit, we can re-construct the test data and even can forecast it at various time instances and varied sampling rates. The idea is similar to exploratory data analysis (EDA) used in statistics, an approach to analise data sets to summarize their main characteristics with visual methods. Curve fitting residuals were used to figure out the system parameter changes as the system is physical with limited bandwidth and cannot respond to high frequency data beyond its bandwidth. Curve fitting parameter was perturbed to verify for sensitivity.

1.3. Hadamard product

The Hadamard product (also known as the Schur product) or the entry wise product is binary operation that takes two matrices and multiply them element wise. $(AoB)_{ij}$ is defined as A_{ij} X B_{ij}. (Horn, 1990) has discussed the Hadamard product in detail. This product proposed by French mathematician Jacques Hadamard and German mathematician Issai Schur. The mathematical properties of the Hadamard product are elaborated by Horn in 1994. Hadamard product's applications in both statistics and physics were discussed by (Horadam, 2007). The advantage of such product in comparison with other counterparts is that, the matrix retains its order even after the product and represents the whole data and retains individual element wise information. Whereas in other matrix operations the order of matrices change.
A tutorial on higher order statistics for signal processing applications is explained by (Mendel, 1991). In case of statistical moments, the whole data is represented by scalar quantities like mean, variance, skewness or kurtosis, to compare test data distributions with standard distributions like normal distribution. This is qualitative comparison analogous to kurtosis (fourth order moment) in diagnostics of bearings. The 4th-order moment (kurtosis) can be interpreted as "relative importance of tails versus shoulders in causing dispersion". (Robert, 2016) explained quantile measures of kurtosis, peakedness, and tail weight and their inferences. (Kevin & McGillivray, 2012) presented a critical review of kurtosis. In present work, Kurtosis was used to amplify the information and suppress the noise. But to retain the temporal information, the fourth order moment was taken point wise, using Hadamard product. In order to retain temporal information the same is needed to be done on short intervals. By using Hadamard product, the whole data was raised to fourth order point wise without losing any temporal information.

For aiding mode loads, the methodology was worked out based on data of four independent channels in static test. Its applicability to actual flight data was verified by comparison study on static test data and static test dry run data (where gas dynamic loads were absent). The applicability of method to failures in opposing mode loads was proven in lab level tests conducted on three samples of jet vanes. The method is able to overcome the problem of attenuation of load effects on motor current due to mechanical advantage of transmission mechanisms. It was also useful in difficult to extract back driving cases, where in the screw jack effect makes motor blind to load dynamics. Method is checked in both aiding (actual static test) and opposing load cases (Lab level tests) for its applicability.

2. STATIC TEST

The thrust vector control (TVC) system consists of 4 channels to steer the flight vehicle. Each channel has a jet vane, deflected by using linear electromechanical actuator (LEMA). This will create side forces and moments resulting in steering of the flight vehicle as desired. The static test of current interest is, a six component test used to arrive at force and moment coefficients as a function of the deflections of jet vanes of thrust vector control system. The same is tested on ground using six component test stand to confirm the sufficiency of TVC system. (Wong et al., 2003) have discussed in detail the calibration and procedure of the six component test in national technical information service of NASA center for aerospace information report NASA/TM-2003-212326.

2.1. The static test setup

The six component static test setup schematic is shown in figure1. The rocket motor is mounted on test stand suspended using six links with load cells to measure. The reference coordinate system as per the schematic is, the X axis is the axis of the rocket motor cylinder, Z axis is along gravity, and Y axis is the direction perpendicular to X axis and gravity by right hand screw rule. Link 'P' for measuring axial force generated in X direction by rocket motor, Q and S links for measuring force in Z direction (Fz) and moment (My) in Y direction. The links R and U are used to measure force in Y direction (Fy) and Moment in Z direction (Mz). The moment about the X axis (Mx) is obtained using link T.

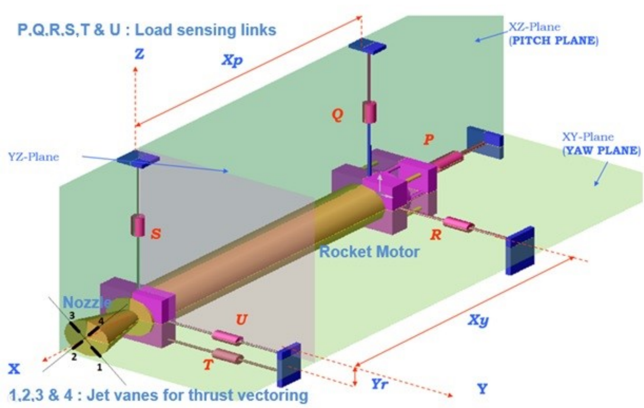

Figure1. Schematic diagram of the static test setup

The three forces and three moment's generation coefficients are calibrated in the test setup by applying known forces and recording readings of all links. In actual test, the rocket motor is fired and jet vanes1, 2, 3, and 4 are deflected as per pre-determined duty cycle as shown in figure 2. The deflections to be given to jet vanes 1,2,3, and 4 are shown as JV1, JV2, JV3 & JV4 respectively in degrees as a function of time. The objective of the test is to arrive at the coefficient matrix which transforms the deflections of four jet vanes into three side forces and three moments generated. The four jet vanes are assembled at the exit of the nozzle and are driven by LEMAs against the gas dynamic loads causing side forces proportional to the angle of deflection. Final utility of the system is in the form where {F} is vector of forces and moments, {d} is vector of four jet vane deflections and [A] is the transformation matrix.

$$\{F\}_{6X1} = [A]_{6X4} X \{d\}_{4X1}$$

2.2. The six component static test

The aim of the six component static test is to arrive at the elements of matrix [A] by commanding known duty cycle to four channel LEMAs {d} and measuring the three forces and three moments from load cell reading at links {F}. The duty cycle is planned to achieve the necessary force and moment coefficients in the of pitch, Yaw and roll directions. The deflection commands to 4 LEMAs are shown in figure 2.

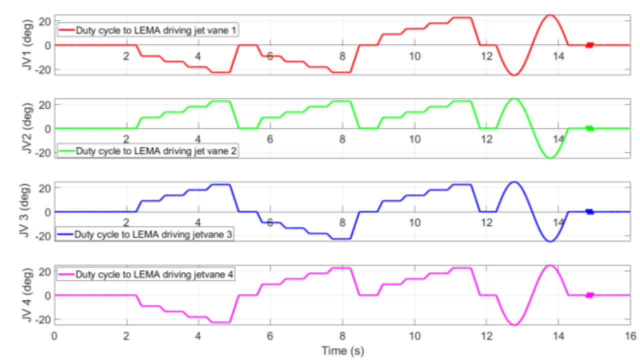

Figure 2. Static test duty cycle for all four jet vanes

From figure 2, the command profile starts at 2 s and till 12 s, it consists of commands to LEMAs resulting in desired pitch, yaw and roll in steps and dwell at each position to facilitate stable measurement of side forces and moments. A sinusoidal command is given during 12 s to 15 s to study the erosion characteristics of jet vanes.

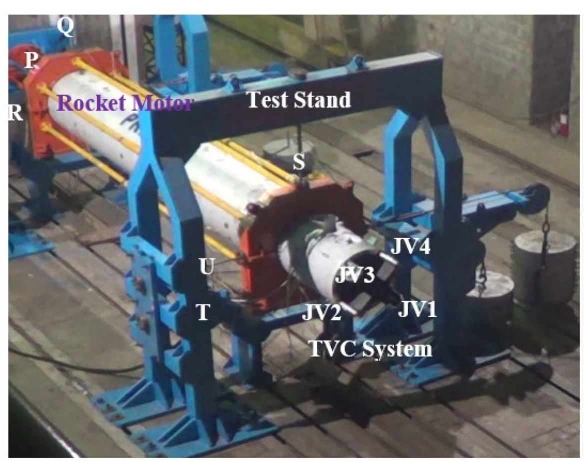

Figure 3. Photograph of six component static test stand

A high frequency low amplitude (15 Hz, 2 deg) command was given to LEMAs to verify the system bandwidth in actual load. Currents during this high bandwidth commands will be comparatively huge, which are plotted in figure 5. The photograph of test stand is shown in figure 3. The rocket motor is suspended in the test stand using six links with load cells. The loadcells designations are marked in figure 3 as explained in schematic diagram in figure 2.

In the static test, The TVC system is sheared off between 4 to 5 seconds (~4.7s). The same is confirmed by the instrumentation of the test stand and high speed video footage. The jet vanes are made of composite material and a photograph at failed cross-section of one of the jet vanes is shown in figure 4.

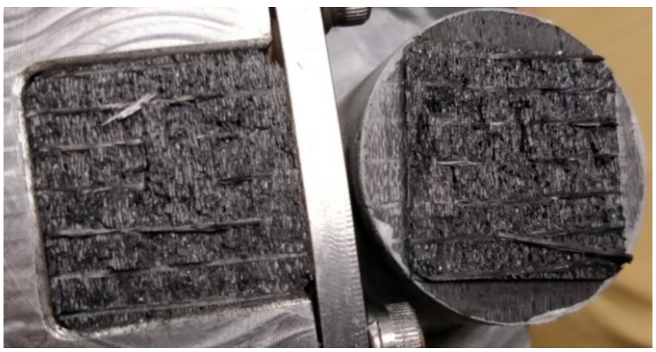

Figure 4. Photograph of cross-section of one failed jet vane

In addition to data of the side force and moment load cells, the LEMA parameters were also recorded. The sampling rate is 5 kHz. The parameters of four LEMAs recorded are, the position command to LEMA, the position feedback from LVDT of LEMA, the velocity feedback from tacho generator of LEMA and the motor current from Linear variable hall effect sensors (LOHET) of LEMA. The data recorded during the static test for all the four LEMAs running jet vanes 1,2,3 and 4 are shown in figure 5. No observable deviation between the commanded and achieved positions of LEMAs is found in any of the four channels. Even the LEMA current data analysis is also clueless of the event.

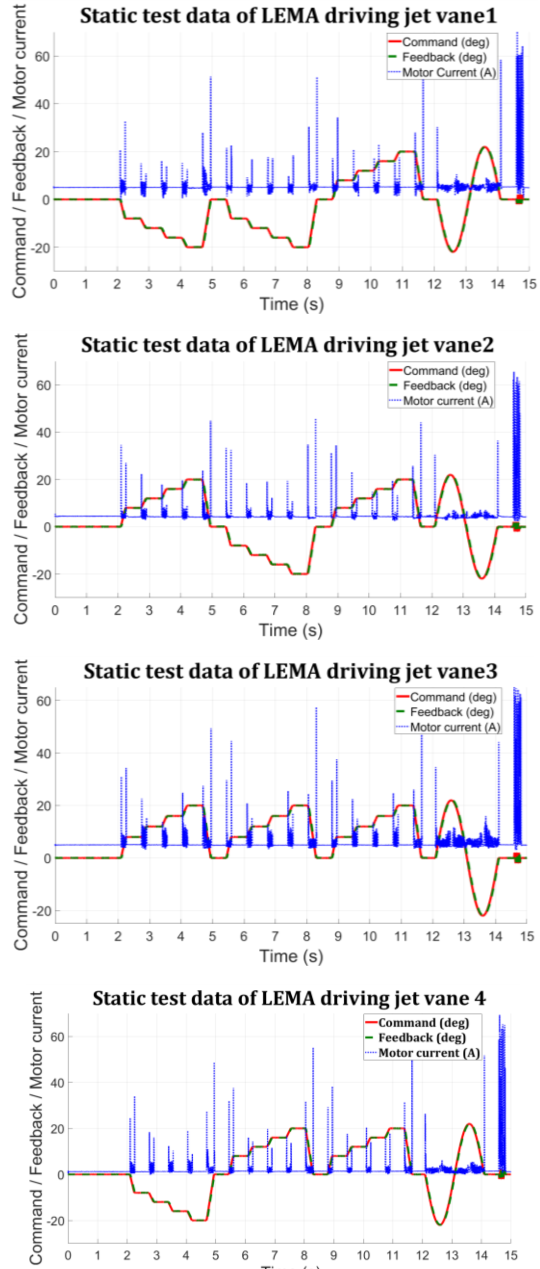

Figure 5. Data recorded during the static test

Current peaks observed in expected period are similar in comparison with similar commands at other time instants. The focused examination of the data extracted from LEMAs in terms of position commands, position feedbacks and currents have shown normal operation.

The test data zoomed into time period of interest is shown in figures 6 & 7.

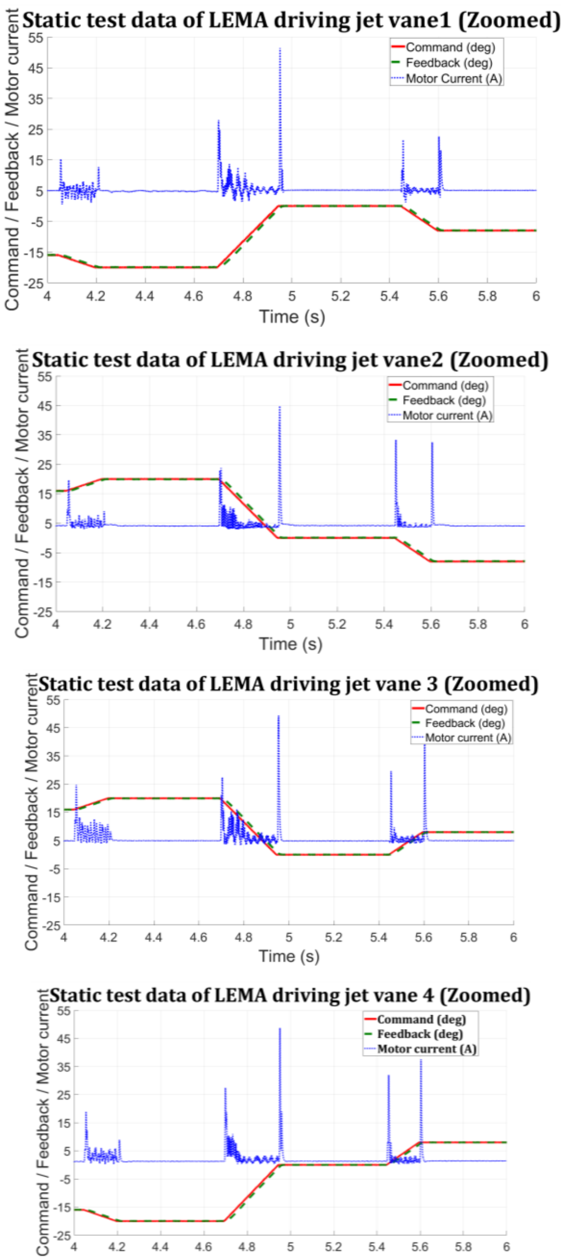

Figure 6. Static test data zoomed to region of failure

3. PROPOSED METHODOLOGY

The current data is shown in figure 7. The failure happened at approximately 4.7s, which is not distinguishable from the current data. The jet vane deflection commands, feedbacks and motor current are acquired from LEMA data acquisition system. There is a current offset, specific to each LEMA based on its parameters and null position. To make comparison across the LEMAs, the current data is processed to zero mean and the same is used for further analysis. It is reassured from this figure that the instances near 4.5, 8.5 and 11.5 s, the input command to all four LEMAs is for full deflection and shearing occurred at first instance, at about 4.5. The same cannot be concluded from LEMA current data as shown in figure 7.

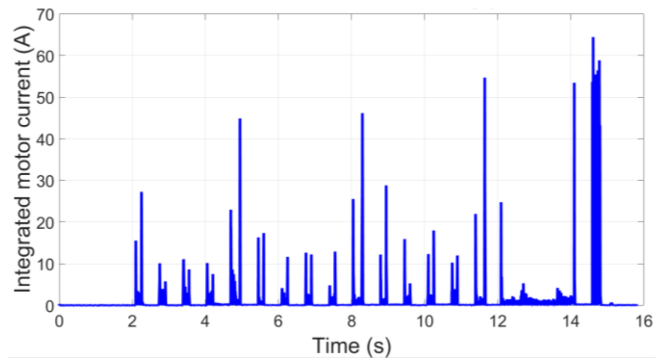

Figure7. Typical motor current of LEMA in static test

3.1 Diagnosis from test data: Numerical integration of the current data is done using cumulative integral command of Matlab and is presented in figure 8. The data at any point represents the current drawn by actuator up to that instant of time and the slope of this data is the actual current drawn at the instant. The integrated current data is easier to interpret and enhanced the correlation to actual physical events, when compared with the direct motor current data. Here, the zero slopes are durations of constant current, ramps are of increasing current and curved ramps are of rapid increasing currents. Such zone of rapid increase of motor current is observed in the region of interest (4-5 s) and is not present at other instances of similar commands, helping in homing on the rapid rate of current increase at instant of jet vane struck position and rapid drop at shear. More detailed and focused examination follows in next section.

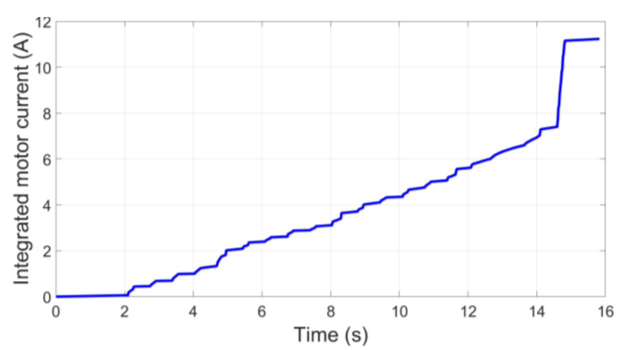

Figure 8.Typical plot of integrated motor current

The smoothing spline with smoothening parameter 0.1 is fit to the cumulative integral data using the Matlab curve fitting tool. The parameter of 0.1 is arrived based on iterative comparison of the degree of smoothness and the computational effort and time required for the fit. A screenshot of the fit and parameters used is in figure 9. The smoothing spline "s" is constructed for the specified smoothing parameter "p" and the specified weights "w_i". The smoothing spline minimizes to equation 1 which is extracted from documentation of Matlab software.

$$p \sum_i w_i (y_i - s(x_i))^2 + (1-p) \int \left(\frac{d^2 s}{dx^2}\right)^2 dx \qquad (1)$$

p is defined between 0 and 1. $p = 0$ produces a least-squares straight-line fit to the data, while $p = 1$ produces a cubic spline interpolant. Quality of fits with various smoothing parameter are given in Table 1. As the data sampling rate is higher (5 KHz) the smoothing parameter has not much effect on the spline fit for values other than 1. To verify the applicability of proposed method, small value 0.1 is chosen.

Fit name	SSE	R-square	DFE	Adj R-sq	RMSE	# Coeff
0.05	1.4781e+03	0.9949	3.1626e+04	0.9949	0.2162	18.9181
0.1	1.1129e+03	0.9961	3.1622e+04	0.9961	0.1876	22.5985
0.2	817.0348	0.9972	3.1618e+04	0.9972	0.1608	27.4529
0.3	659.4807	0.9977	3.1614e+04	0.9977	0.1444	31.2685
0.4	2.6622e+03	0.9908	3.1633e+04	0.9908	0.2901	11.8210
0.5	450.3617	0.9984	3.1607e+04	0.9984	0.1194	38.4099
0.6	365.6508	0.9987	3.1603e+04	0.9987	0.1076	42.4009
0.7	285.2178	0.9990	3.1598e+04	0.9990	0.0950	47.2361
0.8	204.2481	0.9993	3.1591e+04	0.9993	0.0804	53.9057
0.9	117.0080	0.9996	3.1579e+04	0.9996	0.0609	65.7960
1.0	0	1	0	NaN	NaN	31645

Table 1. Quality of fit for various smoothing parameters

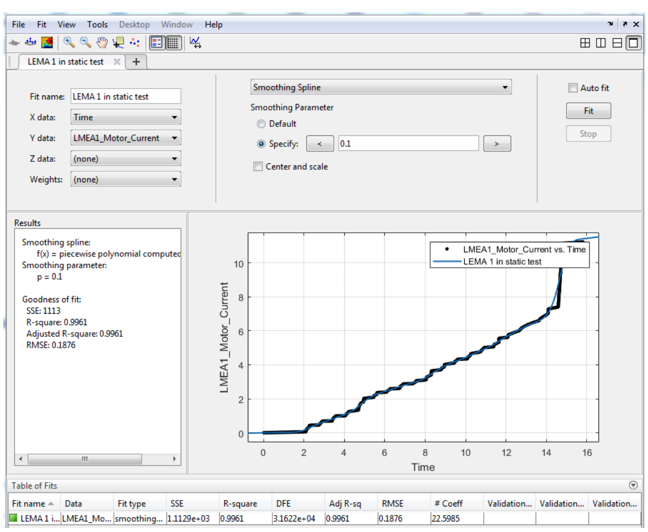

Figure 9. Smooth spline fit to integrated current data

The residuals of the mathematical curve fitted for cumulative integrated motor current of LEMA driving jet vane 1 as a typical case is shown in figure 10. The residuals are higher at the end (after 14 s), pertaining to higher currents drawn by the LEMA for high frequency sinusoidal command at 14.5 to 15 s near its bandwidth which is evident from figure 2.

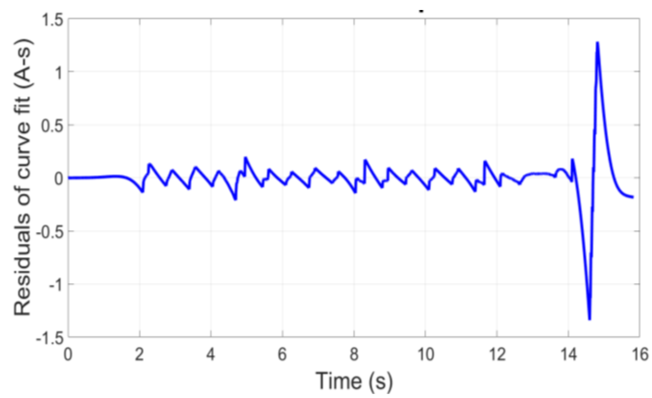

Figure 10. Residuals of the curve fitting

Moments are good way of amplifying the useful information and suppression of the noise similar to kurtosis used in condition monitoring of bearings. The smaller values when raised to higher powers get diminished and higher values will get enhanced (e.g.: 0.1^4, 1^4, 10^4). This technique is applied on residues of the mathematical spline fit to the cumulative integral of LEMA motor currents. By raising residual data points to fourth power, point wise, using Hadamard product, the point wise information is retained. The residues raised to fourth power using Hadamard point product is plotted in figure 11.

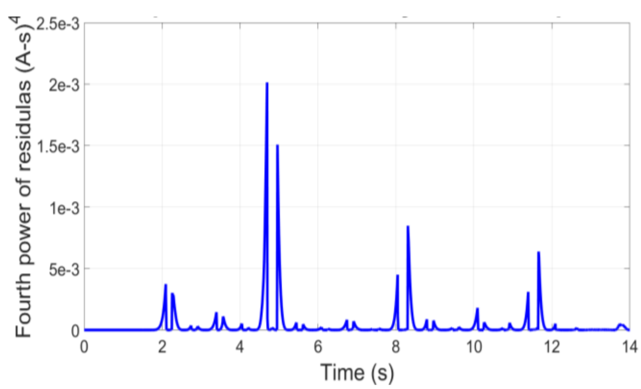

Figure 11. Residuals raised to fourth power by Hadamard product.

The command profile of the static test has intentional high frequency commands near end of test (14 – 15 s) with the corresponding large values of residues, direct plotting of Hadamard product resulted in huge values in that region, masking data in zone of interest. To improve visualisation, the data is normalized within period of interest (0-14 s) and zoomed plot is shown in figure 11. Data covering the event of interest (4.5 -5.0 s) within time interval of 2 to 12 seconds is considered for further analysis.

The normalized amplified residues plot shown in figure 12 from which the error between curve fitted and test data is highest at 4.697 seconds which can be attributed to the event of interest and is also in match with the instance reported by side force analysis done by the static test bed instrumentation.

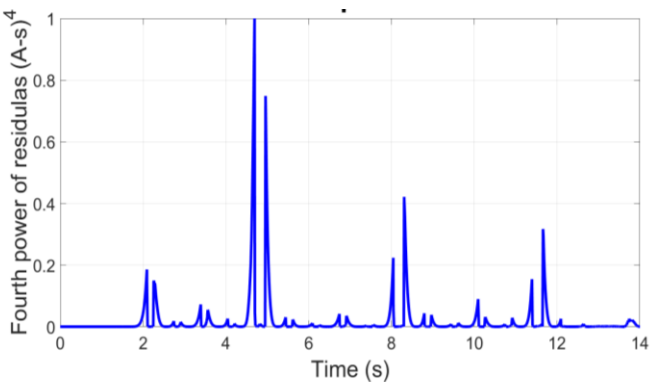

Figure 12. Normalised amplified residues plot

Figure 13 shows the plot of the static test duty cycle of LEMA driving jet vane 1, superimposed on normalised residual error. From the plot it can be concluded that the shearing of jet vane occurred at the instance of 4.7 s when, LEMA commanded return of jet vane from full deflection to zero deflection during time interval 4.5 -5.5 s. A clear peak in residual plot is visible at 4.7 s making it easy to detect the instant of actual jet vane shear. The same information was difficult to make out from other direct means of motor current data visualisation.

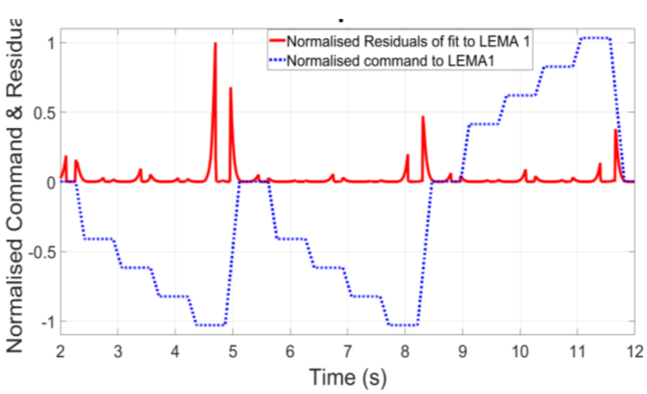

Figure 13.Normalised amplified residues and LEMA 1 command as time reference

The residues at other two instances with similar command has yielded lesser values at instances of 8 and 11.5 seconds reinforcing the conclusion arrived at. The same is evident from zoomed in data for LEMA 1 in the interval during shear (4.6 - 5.2 s) and post failure similar command interval (7.9 - 8.5 s) as shown in figure 14.

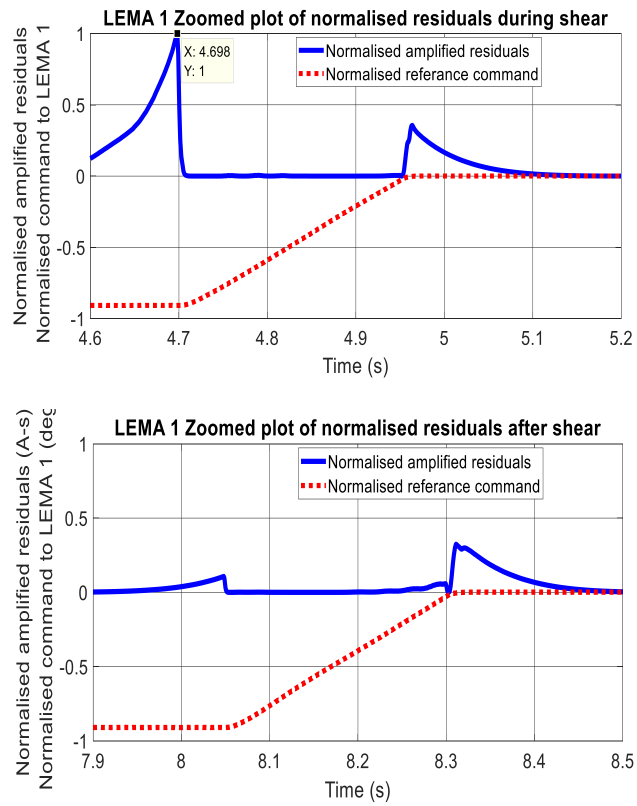

Figure 14. Typical zoomed plot of residues at similar command locations during shear and post shear

The same methodology is implemented on remaining the three channels. The outcome of the data analysis results for all four jet vanes is plotted in figure 15. In all the four channels the failure of jet vanes in shear is pinpointed to a time instance of 4.7 seconds which is in match with the value arrived by other means.

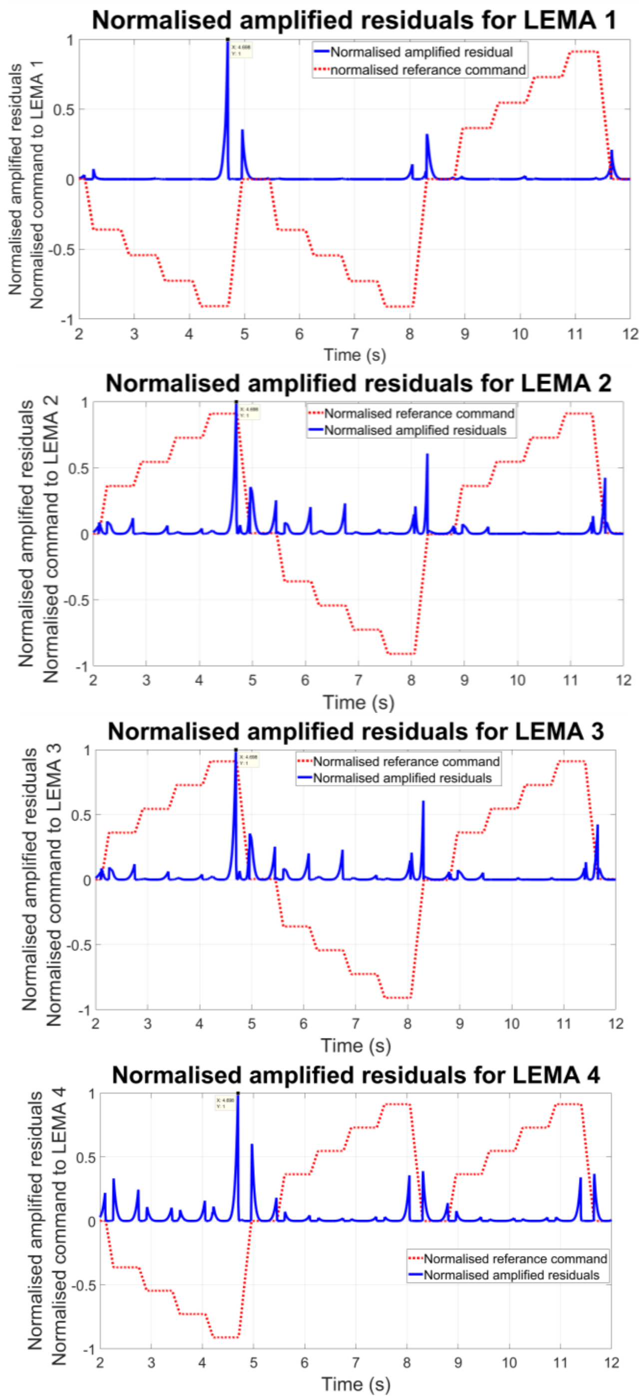

Figure 15. Data analysis results applied to four jet vanes

From the data analysis it is evident that all the four jet vanes sheared simultaneously at about 4.7 s during the event of position commanded from maximum deflection to zero, which is the first instance of occurrence of the maximum load simultaneously applied to all the four jet vanes.

3.2 Diagnostics from the differences between actual static test and dry run data

In actual usage, flight actuation systems work in remote environment and telemetry will be the only data available to assess the performance and their health conditions making excretion of data premium. (Balaban et al. 2010) devised an airborne electromechanical actuator test stand for continuously record data on-board for its prognosis. Due to compact requirements of the system in study, such additional hardware on board is not possible. Hence, an attempt is made to find out the condition of the electromechanical actuators using the already available data in telemetry like position commands and feedbacks and motor currents. Any degradation of actuation system components will lead to an error between command and feedback causing the negative feedback control to actively correct it by pumping more current to the motor which can be detected by careful analysis of motor current.

As the test is ground based, the luxury of dummy runs of exact static test were possible. Just before the static test, to ensure the normalcy of operation and ensuring data acquisition, dry runs mimicking actual test are given and all the LEMAs data was recorded. These runs replicate everything except the gas dynamic load. Hence comparison of the actual test data with the dry run data will be able to give the actual variations occurred due to gas dynamic loads. This can be applied to actual flight data as well. The telemetry of the actual test data will have the LEMA position command, Position feedback and motor current information. The same can be used to mimic the flight profile on ground using in Hardware in loop simulation (HILS). The idea is to apply the methodology discussed in previous section to be applied to the difference between the spline fits made to integrated motor current data from actual test and the simulated test (dry run) on ground with actual dynamics absent. This difference can be used to arrive at in-flight diagnostics as it attributed to the events occurred in flight as a result of flight dynamics.

3.2.1. Methodology adopted

The current drawn by LEMAs driving the four jet vanes of TVC is recorded in both pre-static test dry runs and actual static test. The integrated motor current is arrived at using Matlab command cumtrapz (current data) for data of both dry runs and static test runs. Smooth spline is fit to integrated motor current for each of the LEMAs for both data. The output of the models with time as input is calculated for both dry run and actual test for the period of interest. The difference between the outputs of mathematical smooth spline fit models representing static test and dry runs is arrived at. This difference information is amplified using Hadamard product by raising the residuals to fourth power point wise. Normalizing the data is done to facilitate comparison and arriving at diagnostic information.

The current drawn by motors of all the four LEMAs driving jet vanes in the dry run test conducted before the actual flight is given in figure 16. The motors of all the four LEMAs drawn currents of about 30A during the three instances of full deflection commands at 4.5, 8.5 and 11.5 s.

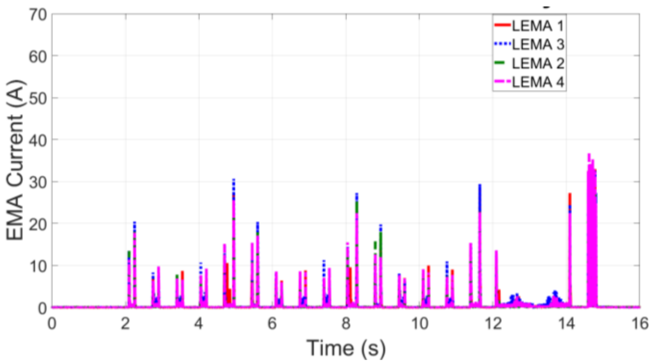

Figure 16. Motor current of all 4 LEMAs in dry run

The current drawn in deflecting all the four jet vanes in the actual static test is given in figure 17. The motors of LEMAs have drawn currents of about 50 - 55 A during the same full deflection commands. The differences in currents drawn by motors of LEMAs between static test and dry run are nearly 20-25 A. These differences in currents drawn are attributed to gas dynamic effects which are present in actual static test alone. All other forces like inertial forces of moving linkage components are same for both static test and dry runs.

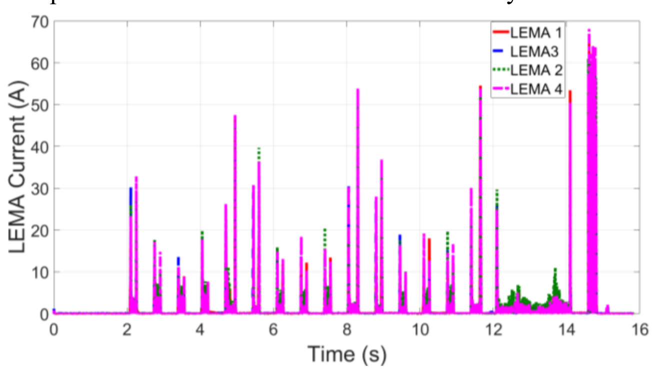

Figure 17. Motor current of all 4 LEMAs in static test

The cumulated integrals of the motor currents of all the four LEMAs in both static test and dry run are consolidated in figure 18. The dry run motor currents are lesser than in actual test as expected.

The data sampling frequency in actual static test is 5 kHz and in dry runs is only 2 kHz. Hence the static test data is sub sampled using Matlab command 'resample'. From figure 18, it is evident that the currents drawn by respective motors of LEMAs driving jet vanes are comparably different in case of dry runs and static test. The integration of the motor current has smoothened the information and improved the visual correlation between the data and diagnostic information. Zooming in the area of interest (4 -5 s) revealed the second order raise of current in case of actual static test, but linear increase in case pre static test dry run.

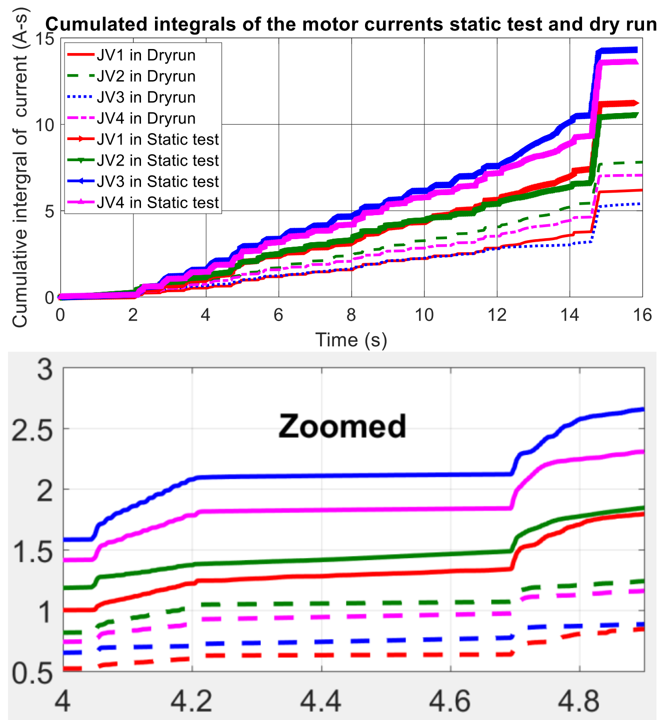

Figure 18. The cumulated integrals of the motor currents of all the four LEMAs in both static test and dry runs

The smooth spline curve fit done to both actual test and dry run test data for jet vane 1 is shown in figure 19. The same is repeated for all other channels and the results are consolidated in subsequent section.

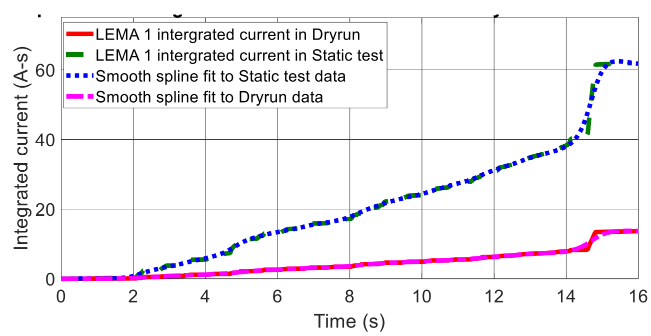

Figure19. Typical plot of curve fit done to actual test and dry run for LEMA of one channel

The differences between the spline curves fit to data of actual test and dry runs consolidated and shown in figure 20.

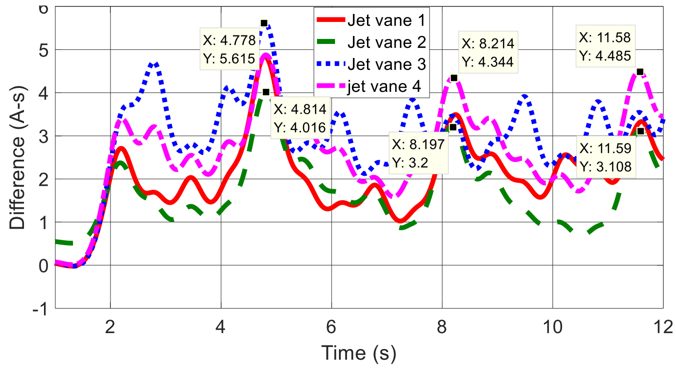

Figure 20. Difference of curves fit to data of actual test and dry run

Jet vanes get eroded as a function of time (approximately 2.8 mm/s) due to sever temperature and gas dynamic forces. The commanded profiles vary for each jet vane resulting no two jet vanes erode with similar rate. Hence, the currents drawn by all the jet vanes is different. To bring them to uniformity, normalizing of the curves is done with reference to the maximum values of the peak in the region of interest. The consolidated plot is shown in figure 21 from which, it is evident that the shear occurred at the instant of 4.8 s in all the four jet vanes. It is in close match with the actual occurrence which happened at 4.7 s as per test stand instrumentation. The smoothening parameter (p) is iterated with finer values (0.2, 0.1 and 0.05) and no change in the time instant is observed making the value independent of smoothening parameter. The recommended value of ‘p’ as per the Matlab documentation is $p \sim 1/(1+h^3/6)$, where ‘h’ is average spacing between data points. As the sampling in present test is done at 5 kHz, $h=2e^{-4}$ making finer values of ‘p’ irrelevant. However, for ‘p’ values nearer to 1 are resulting in large residuals at data start points. Hence the smoothening parameter 0.1 used for analysis in earlier section is used in this data analysis also for uniformity.

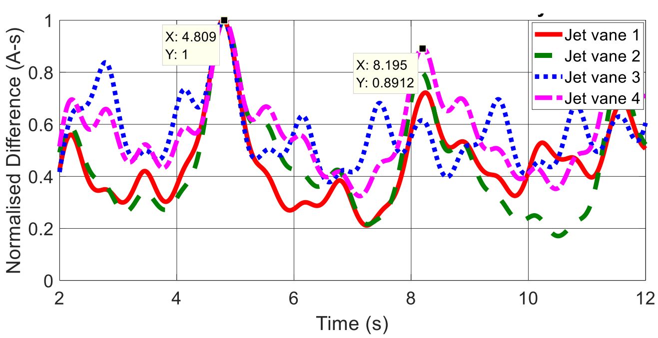

Figure 21. Normalised difference of curves fit to data of actual test and dry run

3.3. Arriving at the diagnostic information in lab level tests

To confirm the test data, lab level test is planned to mimic the jet vane shearing scenario. The jet vane is assembled in the same kinematic configuration as in actual static test. The photographic view of the test setup is shown in figure 22. The following are conditions of the lab test.

The lab test simulated the actual mission kinematics and dynamics excluding aerodynamic and gas dynamic loads.

The temperature effects are not simulated in the test, it is conducted at ambient temperature 25ºC.

The stiffness of the test setup is lower compared to that of the actual test due to larger arms of the mountings to accommodate LEMA assembly.

The effect of inertial dynamics of linkage system is minimized by applying slowest possible LEMA command of 0.1 Hz. The data is recorded at 1 kHz sampling. The lab tests were conducted on three samples. The photograph shows the test setup from both front and back. The LEMA and Jet vane are connected to test fixture through load cells. The jet vane locked in position is driven by LEMA using linkages mimicking the static test.

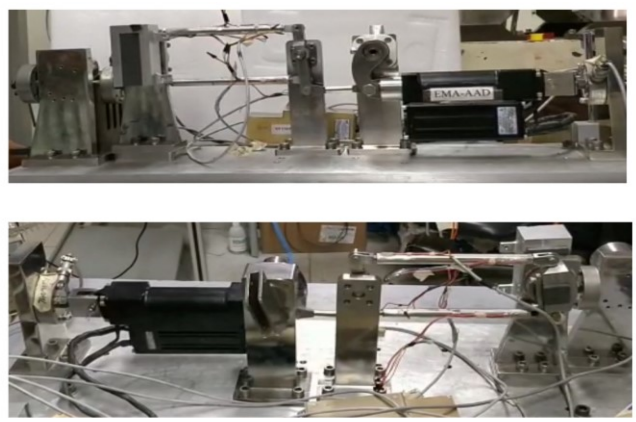

Figure22. Photographic view of the lab test setup

The jet vane is arrested in null position with help of an aluminum enclosure block to avoid localized delamination of Jet vane. The load cell is used to hold Jet vane (J_L) through aluminum block in position and record reaction force data. Another load cell is fitted at the fixed end of actuator (J_L). A sinusoidal command of 20 deg deflection with a frequency of 0.1 Hz is issued to the LEMA to arrive at larger amount of data. As the jet vane is constrained, the jet vane shaft will shear as the load increases beyond its shear strength. The LEMA position command, position feedback and motor current are recorded. Using the same recorder, the test setup load cell readings at both ends (LEMA and Jet vanes) are also recorded. The strain gauges are also mounted on the linkage at a nearest point to the jet vanes for confirmation.

The calibration runs are done with application of known loads and results have shown consistency in terms of jet vane end load cell (J_L) and LEMA end load cell (E_A). To compare data across tests, time synchronization of data is done. The start of the sinusoidal command is adjusted to 1 sec in all the three test data. The consolidated data of tests is given in figure 23.

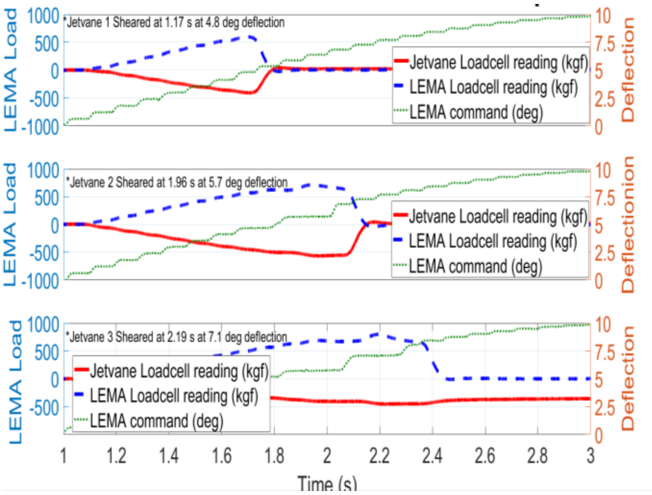

Figure 23. Consolidated lab test data of three samples

The LEMA command is superimposed on load cell data which are at both ends. The LEMA end load cell data of three samples is consolidated in figure 24. The probable instant of failure of the three samples from the load cells data is given in Table 2. As the data from load cells is smooth, exact instance of failure is difficult to be arrived at.

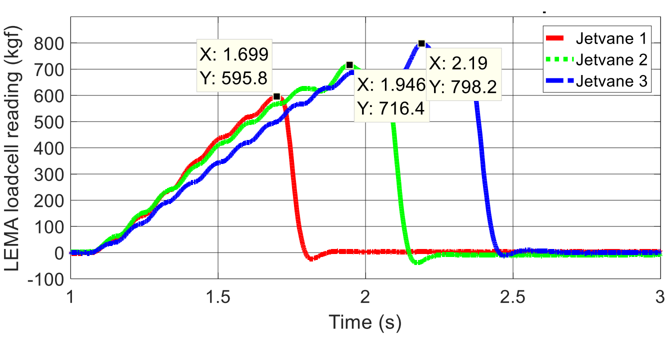

Figure 24. LEMA end load cell data for three samples

Sample No	Instant of shear (s)	Load at shear (kgf)	Torque at shear (Nm)
Jet vane1	1.6-1.7	596	342
Jet vane2	2.0-2.1	716	406
Jet vane3	2.2-2.3	798	454

Table 2. Probable instant of failure of the three samples

The analysis of data is carried out using proposed integrated motor current method. The actual test data plots without any synchronisation was used. As the load is driven by the LEMA, the event of occurrence is visible in current data unlike in the static test where no such clue is visible. This is because the load is generated by LEMA itself and operating in driving mode. The data plots of load cell at actuator end, motor current data and integrated motor current, superimposed on the reference LEMA position command are given in figure 25, figure 26 and figure 27 respectively.

The integrated motor current itself is sufficient to clearly pin point to the event of occurrence of shear. The sudden slope change will clearly pin point the event of occurrence of shear and no further amplification or normalization is found to be needed.

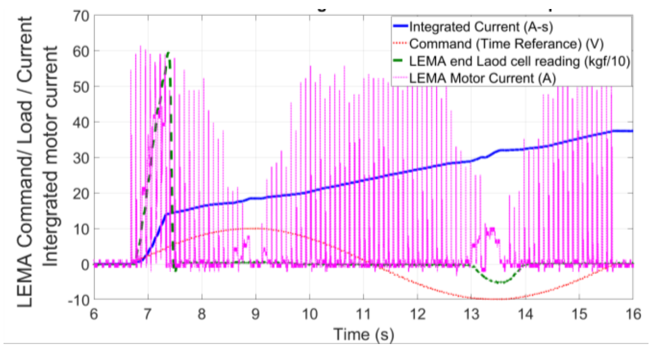

Figure25. Lab test data and integrated motor current for Sample1

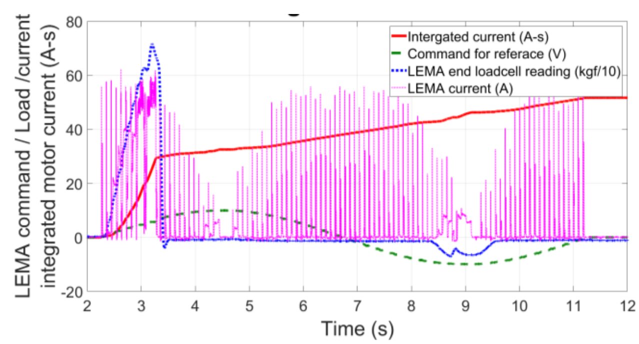

Figure 26. Lab test data and integrated motor current for Sample2

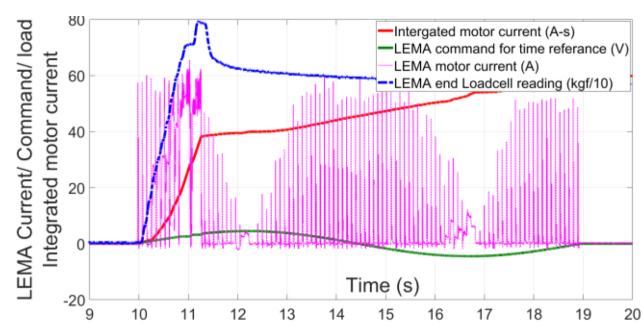

Figure 27. Lab test data and integrated motor current for Sample3

The data acquired during lab tests of three samples are plotted in figure 28. Data is time syncronised for comparison across tests. Position command to LEMA is also plotted to serve as reference. As per the integrated data analysis, the samples thus sheared at 1.641, 2.009 and 2.297 seconds are in close match with the actual values from Table 2.

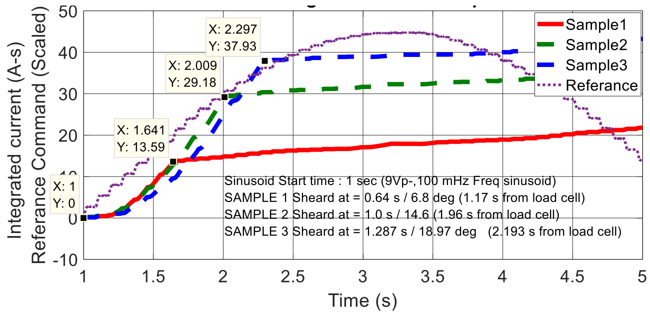

Figure 28. Consolidated results of lab test of all three samples

The reference of start of sinusoid is taken as 1 second in figure 28 for better data visualisation. Practically, the jet vanes, 1,2 and 3 sheared at 0.64, 1.0 and 1.297 seconds respectively relative to the start of sinusoidal command.

4. CONCLUSIONS

The proposed method of diagnostics uses integrated motor current data. It has applications in diagnostics of flight actuation systems driven by LEMAs. Integrated motor current is suitable in case of the failures that are driven LEMA.

In case of the lab level tests, LEMA position feedback and motor current has observable changes at the occurrence of the sudden changes in load. It is due to the fact that LEMA is the driving force generator. The opposition caused by the load is directly seen as load by the motor and at instant of shear the load drops suddenly causing the sudden drop in LEMA motor current. This results in an observable change in position feedback of the LEMA. It is not sufficient to exactly pin point event of occurrence, but the integrated motor current data is able to clearly pinpoint to the event of occurrence.

Whereas in case of failures that are generated by aerodynamic or gas dynamic loads, further processing is required. The diagnostic information is attenuated in the transmission systems due to their mechanical advantage. Such failures can be diagnosed by further analyzing the integrated motor current data by raising it to fourth power using Hadamard product and normalising.

The same technique can also be extended to post flight diagnostics analysis. The actual flight runs can be mimicked on ground by HILS tests and diagnostics of events occurred in actual flight can be arrived by using the proposed method. The diagnostics information can be extracted by applying Hadamard product to the difference between the actual flight and HILS data.

In static tests, the load is applied by the jet and reaches LEMA through multiple mechanical links with mechanical advantage. Hence the load dynamics are attenuated during their passage through various mechanical elements. Hence the necessary change of current at motor level is much smaller making it difficult to observe directly from motor current data.

In actual missions the load is bi-directional. The maneuver demands are initiated from LEMA and will reach control surfaces through mechanical linkages and the disturbances travel back and gets attenuated in the linkages due to mechanical advantage and will not be easily observable by direct data acquired from LEMAs. Hence the information of interest explaining the in-flight events in combination driven in both directions can be extracted from proposed integrated current data which will be of great use in case of arriving at condition monitoring of the LEMAs health from telemetry data of flight vehicles.

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NOMENCLATURE

[A]	Matrix A
{x}	Column Vector ‘x’
ASL	Advanced Systems Laboratory
BLDC	Brush Less Direct Current
DRDL	Defence Research & Development Laboratory
EDA	Exploratory data analysis
E_L	Reading of load cell fixed at actuator
FFT	Fast Fourier Transform
Fx	Force in direction of X axis
J_L	Reading of load cell fixed at jet vane
LEMA	Linear Electro Mechanical Actuator
LOHET	Linear Output Hall Effect Sensors
LVDT	Linear Variable Differential Transformer
MCSA	Motor Current Signature Analysis
Mx	Moment about X axis
PWM	Pulse Width Modulation
RCI	Research Centre Imarat
REMA	Rotary Electro Mechanical Actuators
TVC	Thrust Vector Control

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