Integrated Prognostics Observer for Condition Monitoring of an Automated Manual Transmission Dry Clutch System

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ABSTRACT

The closed loop feedback control system of an Automated Manual Transmission (AMT) electro-pneumatic clutch actuator is used for intelligent real time condition monitoring, enhanced diagnostics and prognostic health management of the dry clutch system, by integrating with the existing gearbox prognostics observer. The real-time sensor data of the clutch actuator piston position is analyzed for monitoring the condition of the clutch system. Original parameters of the new clutch are stored in the Electrically Erasable Programmable Read-only Memory (EEPROM) of the AMT controller and the real-time data is used by the observer for assessing the degradation/wear of the frictional clutch parts. Also, clutch slip during torque transmission is monitored, using the engine speed and the gearbox input shaft speed from Controller Area Network (CAN). Condition monitoring of clutch system provides enhanced prognostic functionality for AMT system which ensures consistent clutch performance, gear shift quality and timely warning for recalibration, repair and/or replacement of the critical wear and tear parts. Also, systematic analysis of the monitored data provides an accurate diagnosis of a developing fault. Thus, with the advanced control systems in place for AMT, a closed loop feedback based condition monitoring system is modelled for improved diagnostics and prognostics of AMT clutch system.

1. INTRODUCTION

Automated Manual Transmission (AMT) is an advanced “Shift by wire” technology which is integrated on a conventional manual transmission (MT). An AMT system which uses a dry clutch, a base gearbox (same as MT), and an embedded dedicated transmission control system that uses electronic sensors, processors, and actuators to actuate clutch & gear shifts is as shown in Figure 1. It does not require clutch pedal actuation or gear shifting by the driver. Clutch controls of an automobile equipped with AMT system is integrated in the accelerator pedal and there is no separate pedal for clutch (two pedal vehicles). Once the driver’s intention to launch the vehicle (forward or reverse) is sent by the accelerator pedal sensor, the AMT electronic controller takes over the automated actuation of the electro-pneumatic clutch actuators. Clutch controls for further gear changes (upshift and downshift) is synchronized along with the gear shift actuation and automatically done by the AMT controller, with no intervention of the driver. The optimal timing and torque required for a smooth clutch engagement is based on input from the sensors and other parameters such as engine speed, vehicle speed & driver’s demand via accelerator pedal. The assembly of typical dry clutch System used in AMT system is as shown in Figure 1.

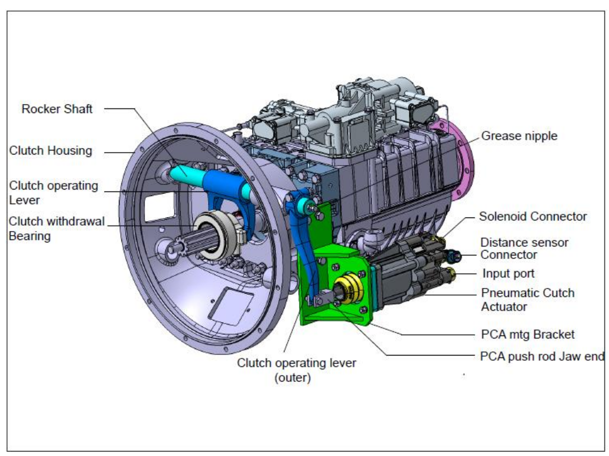

Figure 1. Assembly of gearbox & dry clutch system used for AMT

Dry clutch mechanism of the AMT system is same as conventional Manual Transmission (MT) but the clutch master and slave cylinders actuated by the driver using clutch pedal are replaced by an electro-pneumatic actuator which is mounted directly.

Clutch actuator cylinder is integrated with solenoid to form a single unit and gets mounted over transmission bell housing. The actuator plunger will be directly facing the clutch release fork for clutch disengagement and engagement. Clutch booster, Master cylinder and clutch pedal used for actuation of Manual transmission are deleted and replaced by an electro-pneumatic actuator (with inbuilt stroke sensor) as shown in Figure 2.

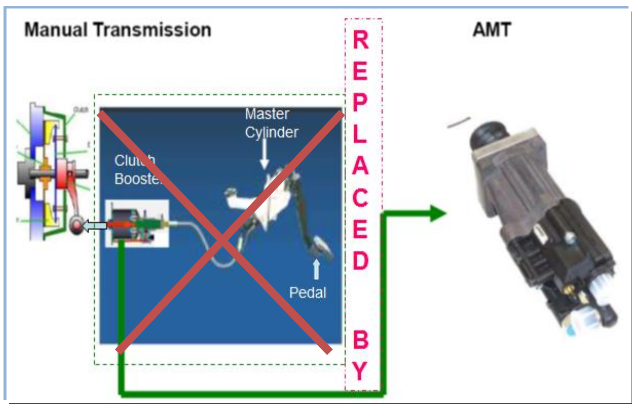

Figure 2. Differences between MT and AMT clutch actuation.

Hall Effect sensors sense the direction of requested shift, and this input, together with a sensor in the gear box which senses the current speed and gear selected, feeds into a central processing unit. This unit then determines the optimal timing and torque required for a smooth clutch engagement, based on input from these two sensors as well as other factors, such as engine speed, vehicle speed & driver's demand via accelerator pedal.

The central processing unit powers an electro-hydraulic, electro-pneumatic or electric actuation unit to either engage or disengage the clutch, which is kept in close synchronization with the gear-shifting action the driver has started. In some cases, the hydro-mechanical unit contains a servomotor coupled to a gear arrangement for a linear actuator, which uses brake fluid from the braking system to impel a hydraulic cylinder to move the main clutch actuator. In other cases, the clutch actuator may be completely electric or working on the compressed air available in the truck.

The power of the system lies in the fact that electronic equipment can react much faster and more precisely than a human, and takes advantage of the precision of electronic signals to allow a complete clutch operation without the intervention of the driver.

The clutch is really only needed to get the car in motion. For a quicker upshift, the engine power can be cut, and the collar disengaged until the engine drops to the correct speed for the next gear. For the teeth of the collar to slide into the teeth of the rings, both the speed and position must match. This needs sensor to measure not only the speed, but the positions of the teeth, and the throttle may need to be opened softer or harder. The even-faster shifting techniques like power shifting require a heavier gearbox or clutch or even a dual clutch transmission.

2. PROGNOSTICS

Real-time condition monitoring of automotive systems has gained popularity in the last two decades for providing lower cost of ownership with prognostic product features. Systematic analysis of the monitored data provides a diagnosis and prognosis of any developing fault. It is an evolving domain with the advanced control and sensor technology but the methodology is yet to be matured for many automotive applications like AMT.

ISO 13381-1:2004 provides guidance for the development of prognosis processes. It is intended to allow the users and manufacturers of condition monitoring and diagnostics systems to share common concepts in the fields of machinery fault prognosis; to enable users to determine the necessary data, characteristics and behavior necessary for accurate prognosis; to outline an appropriate approach to prognosis development; and to introduce prognoses concepts to facilitate the development of future systems and training.

Potential uses for prognostics are in condition-based maintenance. The discipline that links studies of failure mechanisms to system lifecycle management is often referred to as prognostics and health management (PHM), sometimes also system health management (SHM) or - in transportation applications - vehicle health management (VHM) or engine health management (EHM). Technical approaches to building models in prognostics can be categorized broadly into data-driven approaches, model-based approaches, and hybrid approaches.

Predictive diagnosis or Prognosis is a difficult task requiring precise, adaptive and intuitive models to predict future machine health states. Kothamasu, Huang, and VerDuin (2006) reviewed the philosophies and modeling techniques that focus on improving reliability and reducing unscheduled downtime by monitoring and predicting machine health.

Vachtsevanos, Lewis, Roemer, Wu, and Hess (2006) proposed model based approaches that are based on analytical redundancy whereby an input or output can be calculated by using only other inputs or outputs. The quantitative model represents mathematical and functional relationship between the inputs and outputs of a system, while the qualitative models represent qualitative functions.

Sankavaram, Kodali, Pattipati, Singh, Zhang and Salman (2016) presented a novel approach for fault prognosis problem in coupled systems by combining three types of data, i.e., failure time data, static environmental and status parameter data, and dynamic data. There are many prognostic approaches but the taxonomy is not clearly defined and consensually agreed yet. Researchers who are not very familiar with this could get lost in the number of different models and approaches.

Andrew, Daming, and Dragan (2006) summarize and review the recent research and developments in diagnostics and prognostics of mechanical systems implementing Condition-based maintenance (CBM) with emphasis on models, algorithms and technologies for data processing and maintenance decision-making. The authors also discuss different techniques for multiple sensor data fusion and current practices and possible future trends of CBM.

Coble, and Hines (2011) presented the General Path Model (GPM) method used to extrapolate a prognostic parameter curve to a predefined critical failure threshold to obtain an estimate of the Remaining Useful Life (RUL). Technical prognosis as compared to technical diagnosis is still not well charted and explored and is relatively new area of interest as seen from conference papers and journals dealing with this problematic technology. It is still evolving engineering field that is struggling with limited number of real deployments. Various condition-monitoring techniques like vibration analysis, wear debris analysis, thermography, corrosion, acoustic emission with ultrasound, oil analysis and machine performance are adopted for prognostics.

Recent developments show that the new methods like neural networks and fuzzy decision trees provide satisfactory results. Also, significant development and new use-cases of model-based prognosis which will provide better access to more complex physical models. There is still a lack of real deployment and applications and even the taxonomy of methods is not well established.

Although a lot of patents have been registered and a lot of journal/conference papers have been published the area of technical prognosis is still quite new and not well researched, especially robust real system applications are still missing. The main items of current research topics in area of technical prognosis: Metrics for RUL Estimation, Prognostics Methods Classification and Prediction Frameworks by Krupa (2013).

The variety of potential prognostic tools as well as the diversity of published works is of good omen for industrials that may be interested in using such technologies. However, knowing that techniques are suited to the prediction problem is not sufficient to make a choice: Otilia, Rafael, Florin, Eugenia, and Noureddine (2009) suggest that one must have a closer look on implementation requirements and constraints.

The idea of automotive “prognostics” (a combination of prognosis and diagnostics) to determine remaining useful life is not new. Al-Atat, Siegel, and Lee (2011) developed a fault diagnosis method based on a distance calculation from normal along with specific features correlated to different fault signatures is used to diagnosis specific faults. The fault diagnosis method is evaluated for the diagnosis of a gear tooth breakage; input shaft imbalance, bent shaft, bearing inner race defect, and bad key, and the method could be further extended for other faults as long as a set of features can be correlated with a known fault signature.

The hybrid approach considered for AMT system prognostics combines the best of both data-driven and model-based approaches. Some aspects of the data-driven approach are included in the model-based approach. Also, the data-driven approach garnered information from the models.

Condition monitoring of systems for prognostics has gained popularity in recent decades due to potential savings in operating costs and higher reliability. The recent research and developments in diagnostics and prognostics of mechanical systems detailed by Andrew, Daming, and Dragan (2006). include techniques like multiple sensor data fusion and condition-based maintenance (CBM) with emphasis on models, algorithms and technologies for data processing and maintenance decision-making.

Condition monitoring of the AMT dry clutch system provides enhanced prognostic functionality and ensures consistent quality of clutch engagement, clutch disengagement and gear shift. Also, systematic analysis of the monitored data provides an accurate diagnosis of a developing fault in the system. Clutch System real time data monitoring, condition monitoring and clutch prognostics features are integrated with the existing gearbox prognostics observer of AMT system.

Tanaka, and Wada (1995) present a fuzzy control system for the clutch engagement of an automated manual transmission. The fuzzy system is skillful to estimate the driver's will from the accelerator pedal operation. The servo mechanism is mounted on a commercial vehicle and the system parameters are set up by bond graphs simulation and empirical performance tests are carried by using an oil-hydraulically operated engine-vehicle testing rig

3. AMT CLUTCH PROGNOSTICS

Since the AMT system is automated and there is no driver intervention, closed loop condition monitoring of the gearbox would be helpful in effective diagnosis and prognostics of the system. It can also help to prevent the unforeseen breakdown or repairs due to consequential damages. Parker, Carley, Barron, and Dubois (1993) specified generic fault detection, isolation, and estimation architecture using neural network-based fault pattern recognition in transmissions. Systematic analysis of the monitored data provides a diagnosis and prognosis of any developing fault.

Closed loop control of the automated manual transmission system integrated with condition based monitoring, for clutch system needs to be modelled, simulated & calibrated for optimizing the shift controls of AMT electro-pneumatic clutch actuation system considering below listed targets:

- Minimize wear of parts by periodical re-calibration.
- Ensuring consistent shifting quality and comfort.
- Optimizing shifting duration for improving drivability

A fully automatic (AT) transmission deploys prognostics by fusing a degradation model with the pre-lockup feature from measurement, under the extended Kalman filtering framework developed by Ompusunggu, Make, Belgium, Papy, and Vandenplas (2015). A condition monitoring method for wet friction clutches that can be used in real-life applications has been developed and discussed in this paper. The method is based on monitoring the change of the relative velocity signal measured between the input and output shaft of a clutch.

4. PROGNOSTIC METHODOLOGY

Prognostics methodology developed for AMT system is unique and provides simplified measurement and experimentally validated algorithm using lookup table incorporated in the prognostics module of the AMT controller.

Matthew and Wenbin (2010) proposed an approximate methodology using extended Kalman-filtering and condition monitoring information to recursively establish a conditional probability density function for the residual life of a component. The conditional density is then used in the construction of a maintenance/replacement decision model. The methodology is applied to a vibration monitoring scenario and compared with alternative models using the case data.

Matej, Jani, Pavle, and Jozef, (2010) presented a statistical approach to estimating the time in which an operating gear will reach a critical stage. This is done based on a dynamic model that relates hidden degradation phenomena to measured outputs. The Expectation–Maximization algorithm is used to estimate the parameters of the underlying state-space model on line. The time to reach the safety alarm threshold is determined by estimating the distribution of the remaining useful life using the estimated linear model.

A gearshift control strategy for modern AMT with dry clutches is designed through a hierarchical approach by discriminating among five different AMT operating phases: engaged, slipping-opening, synchronization, go-to-slipping, and slipping-closing. The control schemes consist of decoupled and cascaded feedback loops based on measurements of engine speed, clutch speed, and throw out bearing position, and on estimation of the transmitted torque explained by Glielmo, Iannelli, and Vacca (2006)

Optimal control of the engagement of a dry clutch is examined by Dolcini, and Bechart (2005) for the driver's comfort. Only the normal force on the clutch disks is considered as controlled input. The resulting analytically derived controller is used in an observer- based trajectory tracking system whose performances have been tested on a highly realistic nonlinear model yielding good results.

Prognostics methodology developed for AMT clutch system is based on real time monitoring of clutch actuator position and clutch slip. Real world vehicle test data is used for providing prognostic alert for replacement of the wear and tear parts of the clutch.

4.1 Clutch disc wear

In the case of a new AMT clutch system when installed on vehicle, the system self-calibrates and stores the learnt values of all defined parameter in EEPROM of the AMT controller. Clutch friction disc wear is estimated based on the change in the home position of the electro-pneumatic actuator. The input data are obtained from sensor data broadcast in the Controller Area Network (CAN) as per Society of Automobile Engineers protocol SAE J1949.

When the wear limit reaches 95% of the useful life, a warning or alert will be given for repair and/or replacement. Prognostic warning with 5% remaining useful life would provide sufficient time for the driver to service the clutch. Clutch wear is uniform during the life cycle, except during the initial bedding-in period. Once clutch slip happens clutch wear will be abnormal and clutch life cannot be estimated. Refer Figure 3 which shows the wear & tear parts of the clutch assembly which is commonly used on both MT &AMT.

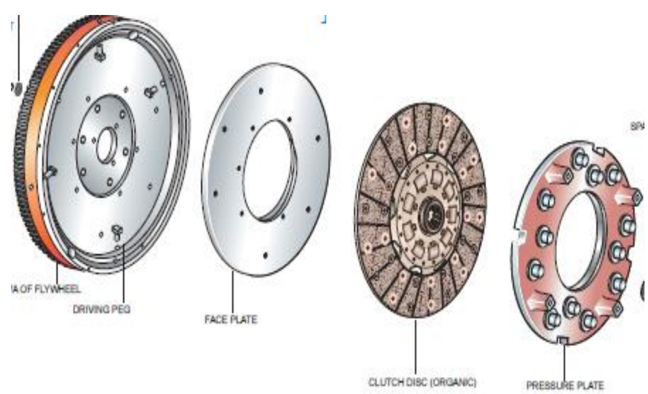

Figure 3. Common clutch assembly used for both MT & AMT

Parthasarathy, Menol, Richardson, Jameel, McNamee, Desper, Gorelik, and Hickenbottom (2008) demonstrated model reduction technique for computing critical component parameters for Remaining Useful Life (RUL). Dynamic neural network model reduces the original model. Data driven prognostic techniques can be applied with minimal error in RUL estimation while taking into account the actual operating conditions.

4.2 Clutch slip

Clutch slip affects the gear shift quality and in turn passenger/driver comfort. This phenomenon happens mainly due to worn out clutch disc and/or contamination of the friction disc with lubricant oil/grease. Clutch slip is calculated using Eq. (1) and the inputs are obtained from sensor data broadcast in the Controller Area Network (CAN) as per Society of Automobile Engineers protocol SAE J1949.

Allowable slip for dry clutch is max 5%. If the clutch slip exceeds the prescribed limit, a warning is given for inspection and repair/replacement of the failed parts. Vasca, Iannelli, Senatore, and Reale (2011) depicted a new model for the torque transmissibility of dry clutches to analyze how the transmissibility characteristic depends on: friction pads geometry, cushion spring compression, cushion spring load, and slip-speed-dependent friction.

Suspect Parameter Number (SPN) 522 as per SAEJ1939 CAN communication protocol describes Percent Clutch Slip as a parameter which represents the ratio of input shaft speed to current engine speed (in percent).
Vehicle Application Layer - J1939-71 (Dec 1999) - p. 55
Data Length: 1 byte
Resolution: 0.4 %/bit , 0 offset
Data Range: 0 to 100 %
Type: Measured
Suspect Parameter Number: 522
Parameter Group Number: [61442]

$$\text{Clutch Slip\%} = \frac{\text{engine rpm} - \text{input shaft rpm}}{\text{engine rpm}} * 100 \qquad (1)$$

5. PROGNOSTIC OBSERVER

The increased use of vehicle sensors for all mechanical and electrical systems, however, provides opportunities for a major expansion of automatically generated prognostics, with contributions from computers in the multiple data buses. Collecting data on engine diagnostics has been present in the fleet industry for years, but using fleet tracking technology to prevent breakdowns before they happen is becoming the new standard for fleet maintenance. GPS devices can be used to track engine hours, odometer readings, idle time, and more. By capturing this fleet data, you can stay on top of fleet maintenance by sending automated service reminders for any type of preventative maintenance.

The need exists to develop an on-board, continuous vibration diagnostic system to detect and to prognosticate faults in these components prior to failure. Lumped parameter models (LPMs) are widely utilised to predict the dynamic behaviour of mechanical systems such as gearboxes. Deshpande, Sawalhi, & Randall (2011) published that LPM gives reasonable representation of the dynamics of the system if masses can be lumped at certain locations, such as gears, shafts, bearings, etc. LPM have the advantage of simulating the structure using a limited number of degrees-of freedom (DOF), which facilitates studying the behaviour of gears and bearings in the presence of nonlinearities and geometrical faults. However, it is difficult to account for the casing flexibility in the LPM model.

Luo, Pattipati, Qiao, and Chigusac (2008) proposed a systems-oriented approach to prognostics requires that the failure detection and inspection-based methods be augmented with forecasting of parts degradation, mission criticality and decision support. Methodology for AMT prognostics observer development includes, Modelling → Simulation → Prognostics → Degradation monitoring → Prediction of remaining useful life → Warning/alert.

The observer is programmed for monitoring the clutch wear and clutch slip during torque transmission. The existing gearbox observer integrated in the AMT control unit is used for condition monitoring of the clutch system. Block diagram of the AMT Prognostics Observer is shown in Figure 4.

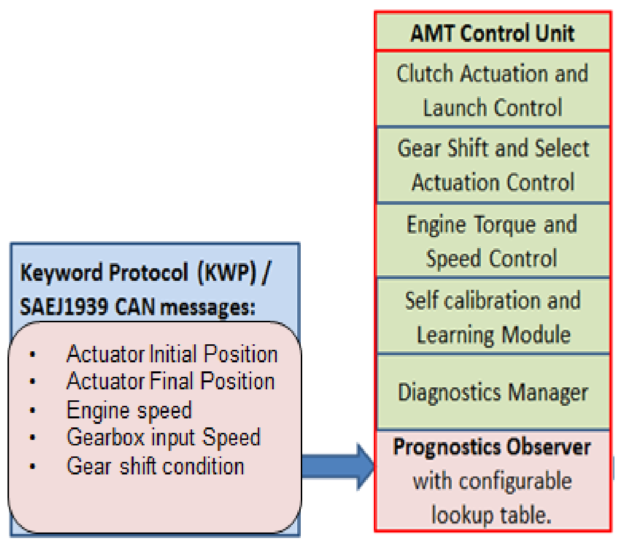

Figure 4. Block diagram of AMT prognostics observer

Jay, Fangji, Wenyu, Masoud, Linxia, and David (2013) provide a comprehensive review of the Prognostics and Health Management (PHM) field, followed by an introduction of a systematic PHM design methodology to select the most appropriate algorithms for specific applications. Visualization tools are presented for displaying prognostics information in an appropriate fashion for quick and accurate decision making.

6. PROGNOSTIC ALGORITHM

The real-time prognostics warning messages from the observer for recalibration and/or servicing can be provided on board and/or off-board for remote diagnostics. Refer Figure 5 for the algorithm used for prognostics of clutch system.

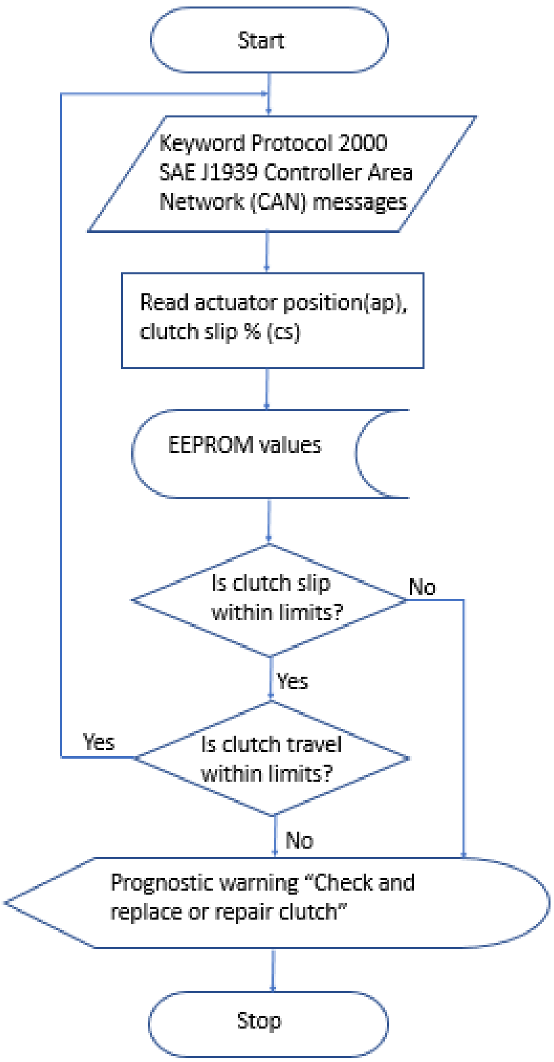

Figure 5. Flowchart for AMT Clutch prognostics algorithm.

Langjord, Kaasa, and Johansen (2011). proposed an adaptive nonlinear observer for an electro-pneumatic clutch actuator which estimates piston velocity, chamber pressures and dynamic friction based on piston position measurement only. Parameter estimations of the clutch load characteristics and friction coefficients are treated through adaptation and the persistence of excitation conditions for convergence of the estimation errors are derived.

Jihong, Chaozhong, and Xing (2010) proposed a systemic prognostics scheme based on neural networks combined dynamic multi-scale Markov model. A performance degradation indicator is designed by multi-feature fusion technique using an FCM algorithm to deal with state division and combining dynamic prediction method and multi- scale theory with Markov model. Further optimizing the weighted coefficient by an optimization algorithm and obtaining more vibration signal data in order to get the actual probability function (PDF) of the remaining life.

The closed-loop control strategy based on experimentally obtained applied force vs. motor position curve and related closed-loop motor position control is presented by Ivanović, Deur, Hancock, and Assadian (2009). A controller algorithm is proposed to compensate for the effect of clutch free-play variations due to clutch wear.

6.1. Prognostic Messages

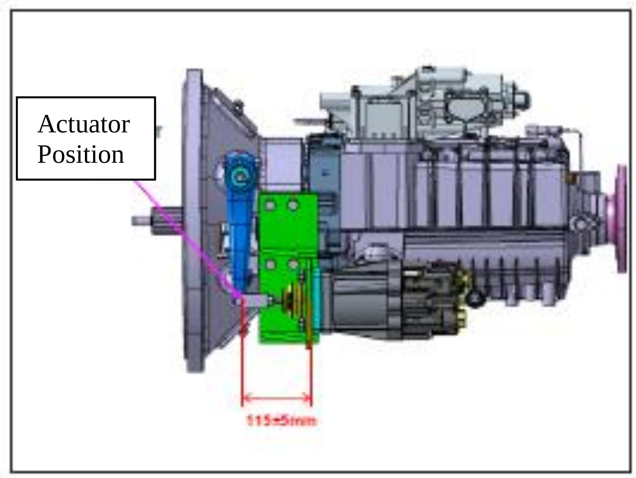

Figure 6. Condition Monitoring of clutch actuator stroke

The initial stand out of Pneumatic clutch actuator push rod is 106.5 ± 6 mm, which is achieved by Pneumatic clutch actuator bracket position.

As the disc wears off, the stand out reduces. When the stand out becomes 78.55 ± 6 mm, reverse the pressure pads in cover assembly. As the vehicle continues to run, the stand out reduces once again. When the stand out becomes again 78.55 ± 6 mm, replace the clutch disc. After replacement of new disc, ensure initial setting of clutch, place the pressure pads in the original position and follow the above procedure.

The main methodological contributions of this work are (i) the proposal of a strategy for selecting the prognostic approach which best suits the information setting, even in presence of mixed information sources; (ii) the development of a boot strap method able to assess the confidence in the RUL prediction in the third case characterized by the unavailability of any degradation observations until failure as detailed by Piero, Francesco, Francesca, and Enrico (2013)

The max wear limit for synchronizer is “x” mm (depends on design) and the prognostics alert/warning message alert is provided when it reaches 0.9x mm. The limit for synchronization force is defined for typical synchronization time of 0.3 to 0.6 second (from experimental data). The real-time prognostics warning messages from the observer for recalibration and/or servicing can be provided on board and/or off-board for remote diagnostics

7. TEST RESULTS

Clutch friction pad wear was closely monitored on five test vehicles which were operated in different city routes in real world usage pattern. Based the wear measurements, useful clutch friction pad life was obtained in the range of 98,000 – 112,000 km.

Parameter	**Route 1**	**Route 2**	**Route 3**
Initial Value (mm)	48.81	48.54	48.94
Real-time value (mm)	33.08	36.11	36.15
Wear Stroke (mm)	15.73	12.43	12.79
Wear %	56.18	44.39	45.68
km covered	58450	48257	53994
Estimated clutch life (km)	98839	103267	112291

Table 1. Summary of accelerated durability field trials

Using the above field trial data captures in Table 1, prognostic warning for clutch replacement is recommended at 95% wear life. Remaining 5% useful life would give ample time and ~ 5000 km coverage, prior to replacement. Also, additional alert can be programmed at 50% wear for clutch pad reversal procedure which is a part of scheduled maintenance.

8. CONCLUSION & FUTURE SCOPE

AMT clutch system prognostics feature could be integrated with the existing AMT gearbox Prognostics Observer controller, for real time monitoring of clutch wear and clutch slip. Using real world test data, warning/alert is given at pre-set limit for checking and replacing the worn out parts. Also, clutch slip is monitored for passenger/driver comfort and consistent shift quality. Closed loop clutch control system is well deployed on Automated Manual Transmission (AMT) for smooth & fast clutch actuation. This ensures minimal torque interruption during launch from stop as well as up and down gearshift, with least jerk or shift discomfort. Also, it is critical for launch of the vehicle on a gradient (uphill or downhill), without any rollback or roll forward due to the unavailability of clutch pedal.

With electronic clutch controls and embedded controller system in place for AMT system, it is possible to incorporate prognostics using closed loop feedback based condition monitoring system to parameters clutch wear, remaining useful life and health of the dry clutch system.

The integrated prognostics observer for AMT clutch system could be further enhanced with automated recalibration of the clutch control system using modelling, simulation & optimization software like Simulink/State flow (MATLAB software from Mathworks).

ACKNOWLEDGEMENT

The authors thank the management of Ashok Leyland Limited, Chennai (India) for sponsoring this research work and arranging the necessary test facilities and equipment. Also, we would like to convey special thanks to Dr Saravanan Natarajan, Head of Engineering, Ashok Leyland.

REFERENCES

Al-Atat, H., Siegel, D., & Lee, J. (2011). A Systematic Methodology for Gearbox Health Assessment and Fault Classification. *International Journal of Prognostics and Health Management, ISSN 2153-2648, 2011 002*

Andrew, K.S., Daming, L., & Dragan, B. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *IEEE/ASME Transactions on Mechanical Systems and Signal Processing, 20,* 1483–1510.

Coble, J., & Hines, J.W. (2011). Applying the General Path Model to Estimation of Remaining Useful Life. *International Journal of Prognostics and Health Management, ISSN 2153-2648, 2011 007*

Deshpande, L., Sawalhi, N., & Randall, R. (2011). Improved Gearbox Simulations for Diagnostic and Prognostics Purposes Using Finite Element Model Reduction Techniques. *Proceedings of the 29th IMAC, A Conference on Structural Dynamics.*

Dolcini, P., & Bechart, H. (2005). Observer-based optimal control of dry clutch engagement. *Proceedings of the 44th IEEE Conference on Decision and Control, Seville, Spain, 2005, pp. 440–445.*

Glielmo, L., Iannelli, L., & Vacca, V. (2006). Gearshift control for automated manual transmissions. *IEEE/ASME Transactions on Mechatronics,11(1)*,17-25

Ivanović, V., Deur, J., Hancock, M., & Assadian, F. (2009). A Closed-Loop Strategy of Active Differential Clutch Control. *Proceedings of ASME Dynamic Systems and Control Conference.2*, 611-618.

Jay, L., Fangji, W., Wenyu, Z., Masoud, G., Linxia, L., & David, S. (2013). Prognostics and health management design for rotary machinery systems; Reviews, methodology and applications. *IEEE/ASME Transactions on Mech Systems and Signal Processing.* http://dx.doi.org/10.1016/j.ymssp.2013.06.004

Jihong, Y., Chaozhong, G., & Xing, W. (2010). A dynamic multi-scale Markov model based methodology for remaining life prediction. *IEEE/ASME Transactions on Mechanical Systems and Signal Processing*. doi:10.1016/j.ymssp.2010.10.018.

Kothamasu, R., Huang, S.H., & VerDuin, W.H. (2006). System health monitoring and prognostics - a review of current paradigms and practices, *International Journal of Advanced Manufacturing Technology, 1012-1024.*

Krupa, M. (2013). Methods of Technical Prognosis – Review", Department of Control and Instrumentation, Brno University of Technology, the Czech Republic.

Langjord, H., Kaasa, G.O., & Johansen, T.A. (2011). Adaptive observer-based switched controller for electro-pneumatic clutch actuator with position sensor. *Proceedings of the IFAC World Congress*, Milan, Italy,

Luo, J., Pattipati, K.R., Qiao, L., & Chigusac, S. (2008). Model-Based Prognostic Techniques Applied to a Suspension System. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, *38*, 1156–1168.

Matej, G., Jani, J., Pavle, B., & Jozef, V. (2010). Model-based prognostics of gear health using stochastic dynamical models. *IEEE/ASME Transactions on Mechanical Systems and Signal Processing*, *Elsevier*, doi:10.1016/j.ymssp.2010.07.003.

Matthew, J.C & Wenbin, W (2010). An approximate algorithm for prognostic modelling using condition monitoring information. *European Journal of Operational Research*, *Elsevier*, 2010, doi:10.1016/j.ejor.2010.10.023.

Ompusunggu, A.P., Make, F., Belgium, H., Papy, J.M., & Vandenplas, S. (2015). Kalman filtering based prognostics for automatic transmission clutches. *IEEE/ASME Transactions on Mechatronics*, *99*.

Otilia, E.D., Rafael, G., Florin, D., Eugenia, M., & Noureddine, Z. (2009). Review of Prognostic Problem in Condition-Based Maintenance. European Control Conference, ECC, Budapest, Hungary.

Parker, B.E., Carley, M.P., Barron, R., & Dubois, T.A. (1993). "Helicopter gearbox diagnostics and prognostics using vibration signature analysis". *Proceedings of SPIE 1965, Applications of Artificial Neural Networks IV, 531*

Parthasarathy, G., Menol, S., Richardson, K., Jameel, A., McNamee, D., Desper, T., Gorelik, M., & Hickenbottom, C.H. (2008). Neural Network Models for Usage Based Remaining Life Computation. *International Journal of Engineering for Gas Turbines and Power*, *130*, 1-7.

Piero, B., Francesco, C., Francesca, M., & Enrico, Z. (2013). Model-based and data-driven prognostics under different available information. *Probabilistic Engineering Mechanics*, http://dx.doi.org/10.1016/j.probengmech.2013.01.003

Sankavaram., C, Kodali., A, Pattipati., K, Singh., S, Zhang., Y, & Salman., M. (2016). An Inference-based Prognostic Framework for Health Management of Automotive Systems. *International Journal of Prognostics and Health Management, ISSN 2153-2648, 2016 009*

Tanaka, H., and Wada, H. (1995). Fuzzy Control of Clutch Engagement for Automated Manual Transmission (AMT). *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility. Vol, 24, 1995, Issue 4-5.*

Vachtsevanos, G., Lewis, F.L., Roemer, M., Wu, B., & Hess, A. (2006). *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*, John Wiley and Sons, Inc. New Jersey.

Vasca, F., Iannelli, L., Senatore, A., and Reale, G. (2011). Torque Transmissibility Assessment for Automotive Dry-Clutch Engagement. *IEEE/ASME Transactions on Mechatronics DOI:10.1109/TMECH.2010.2047509*

BIOGRAPHIES

Ramalingam Sivakumar completed his Masters in Technological Operations from BITS, Pilani (India) in 1995. Currently he is doing research work in the area of Condition Monitoring and Prognostics at BITS, Pilani (Hyderabad, India). He has completed Post graduate diploma in Operations Management from Symbiosis (Pune, India) and is a certified Project Management Professional (PMP) from Project Management Institute (PA, USA). He is a certified Six Sigma Green belt certification from General Electric (USA) and completed Executive Management Program at Great Lakes Institute of Management (India). He is Member (MIE) & Chartered Engineer from Institution of Engineers, (Kolkata, India). Currently he is Head of Product Development Satellite Centre at Ashok Leyland, Pantnagar. He has more than 26 years of total experience in Automotive Industry including few global assignments. His areas of expertise include R&D, Engineering, Product Design, Technology development, Program Management and Product Portfolio Management. His major achievements include development of Mahindra Scorpio SUV, GE locomotives for Indian Railways Modernization Program, Automated Manual Transmission (AMT) for Ashok Leyland vehicles.

Prasad Hanumath V V is currently leading global bus programs for bus platform at Ashok Leyland Limited, Technical Centre, India. He has more than 2 decades of specialization and rich experience in design, development, planning, manufacturing, testing and quality control of automotive clutch systems at leading organization like TAFE. He had led many mission critical projects for improved reliability, performance and life of clutch. He has conducted technical trainings, knowledge sharing sessions and mentoring. He has worked with the author for software development & integration of clutch system for Automated Manual Transmission.

Regalla Srinivasa Prakash obtained his PhD in 1998 on *Evaluation of Boundary Friction under Sub-Surface Plastic Deformation for Metal Forming Processes* from IIT Delhi. He obtained his M.Tech. in 1992 with specialization of Manufacturing science/Mechanical Engineering from IIT Kanpur, where he carried out his thesis work on finite element analysis of steady state cold rolling of strain hardening material. He obtained his B.Tech. in 1990 in Mechanical Engineering from Kakatiya University, Warangal. He has 20 research experience, which includes 17 years of teaching and brief industrial experience. He worked in the Manufacturing Systems Integration Division (MSID) at the NIST, Gaithersburg, Maryland, USA in 1998 as a Guest Researcher, during which he carried out research in the engineering design technologies related to national advanced manufacturing testbed (NAMT). He authored around 50 research papers in reputed journals and conference proceedings and 2 textbooks on design and manufacturing. His current research interests are Additive Manufacturing, Sheet Metal Forming, CAD/CAM/CIM/CAE/PLM, Metalworking Tribology, Medical Device Design and Manufacturing. He is a recipient of the prestigious BIG-5 grant of BIRAC, Department of Biotechnology, Government of India for carrying out research in the area of application of CAD/CAM technologies in medical device manufacturing. He delivered several invited and keynote lectures in reputed conferences including one on recent trends in additive manufacturing at the NTU, Singapore in 2014. He is a member of ASME, TSI, IEI and SAE. Currently he is a Professor of Mechanical Engineering and Associate Dean of Work Integrated Learning Program (WILP) at BITS Pilani, Hyderabad Campus.