ICAST2014 #006

Identification of Aeroelastic Parameters for Helicopter Tail Rotor Limit Cycle Oscillation Monitoring

Yong Chen, Viresh Wickramasinghe and David G. Zimcik

Aerospace, National Research Council Canada, Ottawa, Canada

Abstract

The aeroelastic parameters of helicopter tail rotors are required in the monitoring and evaluation of rotor aeroservoelastic instability incidents such as limit cycle oscillations (LCO). However, in-situ measurement of these parameters on helicopters is generally difficult due to the need to transfer vibration data across a rotating interface. This paper presents a novel center frequency scaling factor relationship of the aeroelastic parameters between the rotating and stationary frames. Together with the stochastic parameter identification technique, this methodology enables real-time estimation and tracking of the critical aeroelastic parameters in the rotating frame during LCO events based on vibration information measured exclusively in the stationary frame. The methodology has been validated using flight vibration data measured from both the rotating and stationary frames of a helicopter tail rotor system during an LCO event. Moreover, this methodology has been applied to the analysis of vibration data measured from the teeter tail rotor system on the Canadian CH-149 Cormorant helicopters to derive the critical aeroelastic parameters during several LCO events.

1. INTRODUCTION

In the development of a new aircraft, the structural modal parameters are typically identified through experimental modal analysis during ground vibration testing (GVT). They are extracted from frequency response functions (FRFs) using appropriate parameter identification techniques, such as the least-square complex frequency domain (LSCF) estimate method [1], polyreference technique [2] and Eigen Realization Algorithms (ERA) [3]. Sine or Sine Dwell tests are sometimes repeated to improve parameter accuracy of closely coupled and lowly damped modes. Flight vibration tests are also performed to validate the analytical models under real flight conditions and, more importantly, to assess the aero-elastic interaction, as a function of airspeed and altitude, between the structure and the aerodynamic forces for flutter clearance. For safety reasons the aircraft must avoid getting into flutter during in-flight test. However it has to demonstrate sufficient flutter margin by flying at different points of the flight envelope. To determine this margin, the trends of frequencies and damping ratios of the critical modes has to be measured as a function of airspeed, and the aeroelastic parameters are identified for each speed though modal analysis using operational vibration data during the flight test.

Similar to fixed wing aircraft, there is a need to estimate aeroelastic parameters for the rotor components in rotorcraft designs to predict performance response and ensure flight safety. However, measurement of these parameters in a rotating frame is generally more difficult due to the need to transfer vibration data across the rotating interface. An example is the need to estimate structural modal and aeroelastic parameters of a helicopter tail rotor in order to establish stability boundaries for flutter and Limit Cycle Oscillation (LCO).

Helicopter tail rotor LCO is a transient high amplitude aeroelastic vibration event which occurs on the tail rotor blade or structures, in a cyclic mode, at the frequency of ωLCO measured in the rotating frame. Because the rotor motion is cyclic, it also leads to the generation of dynamic loads in the stationary airframe at the frequencies of ωLCO-1T known as the regressive mode and ωLCO+1T known as the progressive mode, where 1T represents the nominal tail rotor speed. In general, the LCO is a non-linear phenomenon characterized by a sudden change of aeroelastic damping ratio and frequency due to structure-fluid interactions during flight. The aeroelastic damping ratio typically decreases to initiate the LCO in certain adverse flight conditions and recovers quickly when the conditions change. In such events, reliable knowledge of the aeroelastic damping ratio of the rotating frame structural mode is required in order to determine the appropriate margin of safety for the tail rotor.

Comparing to GVT, the aeroelastic parameters during helicopter tail rotor LCO events have to be estimated based only on output vibration data measured in the stationary frame structure because the aerodynamic loads cannot be accurately estimated during the flight, and furthermore, the transfer of vibration data across the rotating frame is not typically available on in-service helicopters.

In response to the need to estimate aeroelastic parameters for rotating components in the helicopter tail rotor system for structural health monitoring and safety margin assessment, this paper presents a novel center frequency scaling factor relationship of the aeroelastic parameters between the rotating and stationary frames. Together with stochastic parameter identification algorithms, this methodology enables real-time estimation and tracking of the changes of aeroelastic parameters in the rotating frame during LCO events based on vibration information measured exclusively in the stationary frame. The theory will be validated through vibration data measured from both the rotating and stationary frames of a helicopter tail rotor, and then applied to extract the aeroelastic parameters for the teetering tail rotor system of a Canadian Royal Air Force Cormorant helicopter.

2. TAIL ROTOR AEROELASTIC PARAMETER IDENTIFICATION METHODOLOGY

2.1 Translation of Vibration between Rotating and Stationary Frames

During helicopter tail rotor LCO events, the critical mode of the helicopter tail rotor structure is excited by adverse aerodynamic loads at the frequency of ωLCO in the rotating frame. Due to the inherent coupling of tail rotor vibration with the N/rev components of the tail rotor frequency, the dynamic load measured in the rotating frame, H(t), will be modulated by the N/rev tail rotor passage frequencies when transmitted to the stationary frame. Therefore, the dynamic load observed in the stationary frame, F(t), can be expressed as

$$\mathrm{F(t)} = \mathrm{H(t)} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{A_i}\ \cos(2\pi \mathrm{f_i}\ \mathrm{t}) \tag{1}$$

where Ai represents the weight coefficient corresponding to the ith component of the tail rotor passage frequency. Assuming the dynamics of the stationary frame structure is frequency dependent and represented by $\mathrm{B(t)}$, the vibration response $\mathrm{X(t)}$at the tail rotor gear box location, which is measured in the stationary frame of the helicopter tail structure, can be expressed as

$$\mathrm{X(t)} = \mathrm{B(t)} * \mathrm{H(t)} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{A_i}\ \cos(2\pi \mathrm{f_i}\ \mathrm{t}) \tag{2}$$

where * denotes the operation of time domain convolution. The time domain expression of the stationary frame vibration can be transformed into the frequency domain for aeroelastic damping ratio identification using various technical methods such as the classical -3dB approach [4], as listed below

$$X(j\omega) = B(j\omega) \times \sum_{i=1}^{N} [\frac{A_i}{2} H\big(j(\omega - 2\pi f_i)\big) + \frac{A_i}{2} H\big(j(\omega + 2\pi f_i)\big)] \tag{3}$$

This expression demonstrates that due to the modulation with the N/rev harmonics, the dynamic load generated by the LCO at the frequency of ωLCO in the rotating frame is split into multiple sets of paired vibration modes in the frequency domain when translated to the stationary frame.

Considering only the 1/rev tail rotor harmonic, the dynamic load in the rotating frame due to tail rotor LCO vibration is transformed into a pair of vibration peaks in the frequency domain in the stationary frame: one at the frequency of ω_{LCO}-$2\pi f_1$, normally known as the regressive mode and the other at $\omega_{LCO} + 2\pi f_1$ known as the progressive mode, where f_1 represents the frequency of 1/rev tail rotor speed. Therefore, it is important to note that the two peaks observed in the stationary frame are not real structural modes, but derived indirectly from the tail rotor blade mode at the frequency of ω_{LCO} in the rotating frame.

Theoretically the dynamic load introduced by the rotating frame mode would be transformed into two spectral peaks with identical amplitudes and spectral width in the stationary frame when other dynamic characteristics of the stationary frame structure are not considered. In terms of spectral characteristics, it is important to note that the regressive and progressive modes retain the same spectral pattern as the rotating frame mode. However, the amplitude and pattern of the two peaks may be altered due to the interaction with dynamics of the stationary frame structure, i.e. $B(j\omega)$, at the frequency of interest.

Typically the critical mode of the tail rotor structure during LCO events is lightly damped and therefore the spectral width of the resonant peak is generally very narrow. With the condition that the stationary frame structural modes are well separated from the regressive and progressive modes, these two modes would still retain a similar spectral shape as the rotating frame mode. As a result, variation in the amplitude and pattern of the regressive and progressive modes will depend on interactions with adjacent structural modes of the stationary frame structures.

2.2 Correlation of Aeroelastic Parameters between the Rotating and Stationary Frames

Considering the underlying mechanism involved in the vibratory load transmitted from the rotating frame to the stationary frame during LCO events, the aeroelastic parameters of the rotating frame tail rotor mode can be identified based on assumptions: the critical rotating frame mode is lightly damped and has been effectively excited by the aeroelastic load during LCO events; and the resulted acceleration in the stationary frame can provide sufficient signal to noise ratio to enable reliable determination of the regressive and progressive modes.

Typically, the damping ratio of the rotating frame mode is defined as

$$\xi_f = \frac{\Delta f}{\omega} \tag{4}$$

where ω is the frequency of the rotating frame mode and Δf is the -3dB spectral width. Similarly the damping ratios of the regressive and progressive modes can be defined in the stationary frame respectively as

$$\xi_{(\omega-2\pi f_1)} = \frac{\Delta f}{\omega-2\pi f_1} \tag{5}$$

$$\xi_{(\omega+2\pi f_1)} = \frac{\Delta f}{(\omega+2\pi f_1)} \tag{6}$$

The damping ratios of the regressive and progressive modes can be evaluated directly based on the spectral diagram of the stationary frame vibration data. Assuming that the spectral shapes of the rotating frame mode, regressive and progressive modes are similar for the lightly damped tail rotor structural mode according to the mechanism discussed previously, then the spectral width of the two resulting modes can be derived according to equation (5) or (6). Based on equation (3), the frequency of the rotating frame mode can be approximated based on the frequency of the regressive and/or progressive modes, and the 1/rev of the tail rotor speed. Therefore, with known values of the spectral width and frequency of the rotating frame mode, the aeroelastic damping ratio for the rotating frame tail rotor mode can be determined based on the aeroelastic parameters of the paired regressive and progressive modes which can be derived from the stationary frame vibration data directly.

Based on equations (4), (5) and (6), the aeroelastic parameters of the rotating frame mode, regressive and progressive modes are not independent parameters. Rather, the regressive and progressive modes defined in the stationary frame are directly derived from the rotating frame mode through the modulation of the rotating frame vibration with the 1/rev tail rotor speed. Therefore, the aeroelastic parameters of the rotating frame mode can be determined using a center frequency scaling factor relationship as defined below

$$\xi_f = \frac{\xi_{(\omega-2\pi f_1)}}{\omega} * (\omega - 2\pi f_1) = \frac{\xi_{(\omega+2\pi f_1)}}{\omega} * (\omega + 2\pi f_1) \tag{7}$$

It is clearly shown that the aeroelastic parameters of the regressive mode in the stationary frame are scaled from the excited mode in the rotating frame. The scaling factor is defined by the respective center frequencies and expressed as

$$\xi_{(\omega-2\pi f_1)} = \frac{\omega}{(\omega-2\pi f_1)} * \xi_f \tag{8}$$

Similarly the aeroelastic parameters of the progressive mode are also scaled from the rotating frame tail rotor mode by a factor defined by the respective center frequencies, and expressed as

$$\xi_{(\omega+2\pi f_1)} = \frac{\omega}{(\omega+2\pi f_1)} * \xi_f \tag{9}$$

Based on the mechanism in which the rotating frame mode vibration is translated to the stationary frame, it is revealed that the aeroelastic parameters of three related modes are not independent, and the values are scaled by the modal frequencies of the rotating frame mode and the 1/rev tail rotor speed. Therefore, the aeroelastic parameters of the rotating frame mode can be estimated from the information of the regressive and progressive modes, which can be identified directly from the vibration data measured in the stationary frame structure.

2.3 Identification of Aeroelastic Modes

2.3.1 Stochastic Realization Algorithm

Experimental modal analysis methods to identify structural modal parameters are based on frequency response functions which require measurement of applied input as well as the resulting responses due to this input. However, there are scenarios where controlled excitation cannot be applied to extract modal parameters. Other examples are large-scale structures such as bridges and high rise buildings which require impractically high excitations, or aircraft in flight which is already exposed to ambient vibrations while controlled excitation is difficult to implement.

For a random vibrating system, the aeroelastic parameters can be identified from operational and output only data using system identification techniques based on the Stochastic Realization Theory [5, 6]. Considering the stochastic components in the output data, the dynamics of a structure excited by a random input load can be represented by a discrete time state-space model as

$$\begin{aligned} X_{k+1} &= AX_k + BU_k + S_k \\ Y_k &= CX_k + DU_k + V_k \end{aligned} \tag{10}$$

where S_k and V_k are both considered as zero mean white noise, with the expectation of

$$E\left[\begin{pmatrix} S_k \\ V_k \end{pmatrix} \begin{pmatrix} S_k & V_k \end{pmatrix}^T\right] = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix} \tag{11}$$

For a stochastic system, where the excitation U_k cannot be measured, the excitation effect can also be assumed to be represented by the disturbances S_k and V_k. In this case the state-space model of a randomly excited structure is simplified to

$$\begin{aligned} X_{k+1} &= AX_k + S_k \\ Y_k &= CX_k + V_k \end{aligned} \tag{12}$$

The stochastic process X_k is considered stationary and zero mean, and the covariance is expressed as $E\left[X_k X_k^T\right] = \sum$. The noises S_k and V_k are both zero mean, and the output and state-output covariance matrices are defined as

$$\Lambda_i = E[Y_{k+i} Y_k^T], \; i=0, 1, \ldots, N \tag{13}$$

$$G = E[X_{k+1} Y_k^T] \tag{14}$$

Based on these assumptions, the following properties exist [7, 8]

$$\begin{aligned} \sum &= A \sum A^T + Q \\ \Lambda_0 &= C \sum C^T + R \\ G &= A \sum C^T + S \\ \Lambda_i &= CA^{i-1} G \end{aligned} \tag{15}$$

The relationships in equations (15) indicate that the output covariance can be considered as the impulse response of the deterministic linear time-invariant system A, G and C. This implies that the modal parameters of a sufficiently disturbed structure can be extracted when it is subjected to unknown random excitation loads. Details of the stochastic realization algorithm are provided in reference 7 and 8.

2.3.2 Time-Frequency Domain Analysis of Non-stationary Stochastic Signals

Assuming that the helicopter tail rotor structure is subjected to an unknown random aeroelastic load which contains broadband energy, the stochastic realization algorithm provides a practical modal analysis approach to extract the critical aeroelastic parameters of the regressive and progressive modes observed in the stationary frame of the helicopter structure based only on the vibration data measured in operational conditions. Moreover, helicopter tail rotor LCO is a transient and non-stationary process in which the aeroelastic parameters could vary with time. In order to track the variation of aeroelastic parameters during LCO events, the vibration data should be divided into multiple short time segments similar to the concept of the Short-Time FFT method. By applying the stochastic realization algorithm to each short time data segment, and also moving the time window together with the window overlapping techniques, the critical aeroelastic parameters of helicopter tail rotor LCO events can be estimated and tracked to reveal the variation of aeroelastic parameters with time under operational conditions.

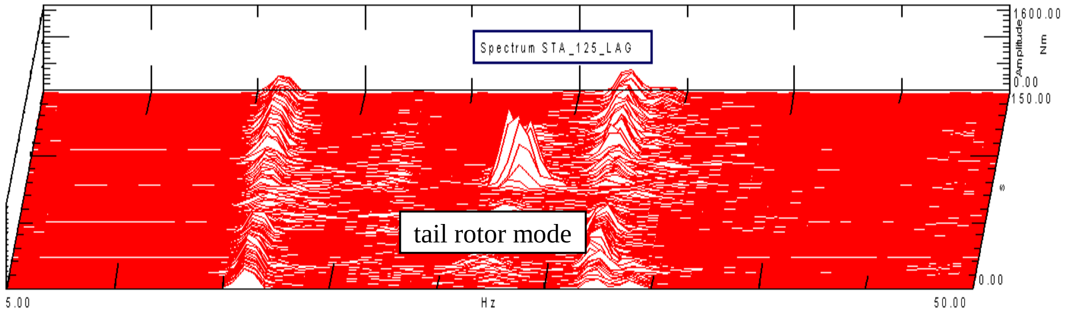
With the center frequency scaling factor relationship and the stochastic realization algorithm to identify modal parameters, the critical aeroelastic parameters in the rotating frame of helicopter tail rotor structures can be estimated based on vibration data measured exclusively in the stationary frame of a helicopter structure. This approach eliminates the need to provide a controlled excitation in the rotating frame of the helicopter tail rotor system which significantly simplifies the need for reconfiguration of the vehicle. The aeroelastic parameters identified from representative LCO measurements would enable the tail rotor stability diagram to be updated and further to evaluate the impact of the LCO on the integrity of helicopter tail rotor structures with a higher degree of confidence.

3. METHODOLOGY VALIDATION WITH HELIOCPTER LCO DATA

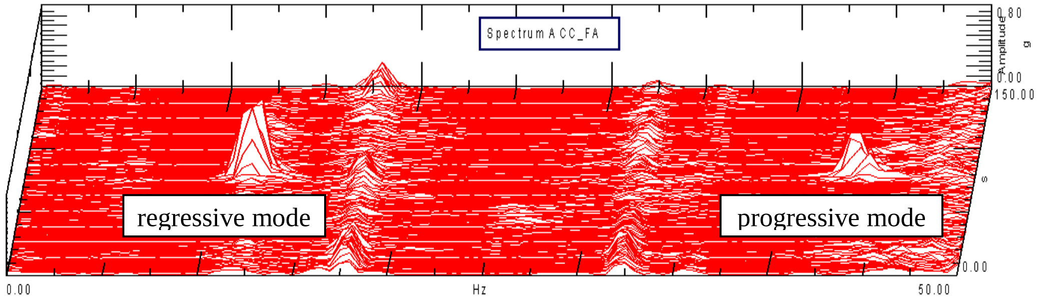
The center frequency scaling factor relationship has been validated using flight data measured on a test helicopter equipped with vibration sensor arrays in both the rotating tail rotor frame and the stationary frame of the tail boom structure. One known LCO event occurred and the vibration data was recorded during a flight test mission and the vibration data was subsequently analyzed. Since the dataset contained vibration responses measured synchronously in both frames, it provided a unique opportunity to identify the aeroelastic parameters in both frames in order to validate the center frequency scaling relationship and stochastic modal parameter identification method.

In the test helicopter, the rotating frame structural response was measured by a strain gauge bonded on the rotor blade, while the stationary frame response was provided by an accelerometer attached to the Fore/Aft (F/A) direction of the tail rotor gearbox. During the LCO event, the critical mode of the rotating frame structure was excited by aerodynamic load and resulted in significant vibration of the rotor blade structures. The vibratory load was transmitted to the stationary frame of the vehicle, and the vibration measured in the Fore/Aft direction of the helicopter tail rotor gearbox also showed increased vibration levels in synchronization with the rotating frame structures. Two vibration peaks, i.e. the regressive and progressive modes, were identified in the stationary frame simultaneously. Both vibration peaks retained the similar spectral features as the excited critical rotating frame mode which confirmed that they were closely related modes resulted from the same LCO event rather than independent structural modes. Waterfall plots of the rotating and stationary frame modes excited in the LCO event are shown in Figure 1, and the time domain vibration data are shown in Figure 2.

For validation purpose, the aeroelastic parameters of the three modes have been evaluated based on the measured vibration data. As shown in Figure 2, the time trace at the top left part of the figure was measured from the rotating tail rotor blade. It was filtered between 25 and 30Hz to show the excited tail rotor mode in the rotating frame. The time trace shown on the top right part of the figure was measured from the tail rotor gearbox in the stationary frame, and the vibration data was filtered in two narrow bands: one band between 10 and 15Hz was related to the regressive mode and the other between 42 and 46Hz was related to the progressive mode. It was observed that the vibration amplitudes of the three modes were synchronized and showed similar dynamic features. The time traces in both frames showed two major oscillation cycles in the LCO event. The stochastic realization algorithm was applied to analyze the vibration data, and the aeroelastic parameters were identified reliably.

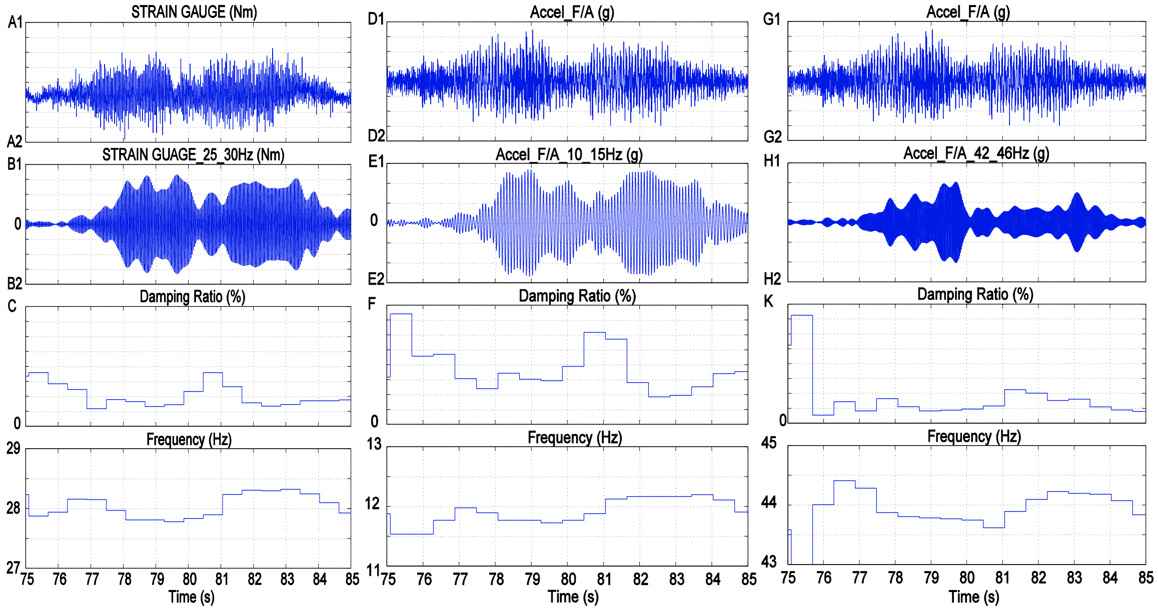


(a) Helicopter tail rotor mode



(b) Regressive and progressive modes measured in the stationary frame

Figure 1. Waterfall plots of the strain gauge and acceleration data during the LCO event



(a) Tail rotor mode (b) Regressive mode (c) Progressive mode

Figure 2. Variation of aeroelastic parameters during the LCO event

By comparing the aeroelastic parameters of the critical tail rotor mode with the regressive and progressive modes in the stationary frame, the trends of aeroelastic parameter variation also showed strong correlation. In the rotating frame, the damping ratio normalized by the nominal value of damping of the tail rotor mode before the excitation, varied between 0.39 and 1.00, while the modal frequency varied between 27.7 and 28.3 Hz. In the stationary frame, the normalized damping ratio of the regressive mode normalized by the same value as above varied between 0.78 and 2.14, while the frequency shifted between 11.7 and 12.2 Hz. For the progressive mode, the damping ratio also normalized by the same value as above, varied between 0.31 and 0.72 while the frequency shifted between 43.7 and 44.4 Hz.

According to the vibration data recorder installed on the helicopter, the tail rotor speed was operating at 16.3 Hz during the LCO event. Based on the identified aeroelastic parameters in the stationary frame, the aeroelastic parameters of the critical tail rotor mode were estimated inversely using the center frequency scaling factor relationship. The aeroelastic parameters of the rotating frame mode were averaged using the information of the regressive and progressive modes. The results are listed in Table 1 for the parameters directly measured from experimental data (EXP) and the parameters estimated using the centre frequency scaling factor (EST). The normalized damping ratio of the rotating frame mode was calculated to vary between 0.41 and 1.02, while the frequency shifted between 27.7 and 28.3 Hz during this transient aeroelastic LCO event. These were sufficiently accurate compared to the aeroelastic parameters identified directly from the vibration data measured in the rotating frame, where the damping ratio varied between 0.39 and 1.00, and the frequency varied between 27.7 and 28.3Hz. The variation in aeroelastic parameters reflected the dynamic coupling effect between the two frames of the tail rotor system of the test vehicle during the LCO event.

Comparing the aeroelastic parameters directly identified from the vibration data measured in the rotating frame and the parameters inversely estimated, it was clearly shown that the aeroelastic parameters of the critical tail rotor mode can be reliably obtained based on the information of the regressive and progressive modes which can be identified exclusively from vibration data measured in the stationary frame.

Table 1. Aeroelastic parameters of the stationary and rotating frames during the LCO event

Modal Parameters	Rotating Frame				Stationary Frame			
	Tail Rotor Mode				Regressive Mode		Progressive Mode	
	Low		High		Low	High	Low	High
	EXP	EST	EXP	EST	EXP	EXP	EXP	EXP
Normalized Damping	0.39	0.41	1	1.02	0.78	2.14	0.31	0.72
Frequency (Hz)	27.7	27.7	28.3	28.3	11.7	12.2	43.7	44.4

It is necessary to note that the critical rotating frame tail rotor mode needs to be excited sufficiently to enable reliable identification of the regressive or progressive modes in the stationary frame. This is an important conclusion regarding the estimation of the critical aeroelastic parameters of the rotating frame mode for the helicopter tail rotor structures during LCO events. A viable estimate of LCO parameters in the rotating frame can be obtained from vibration sensors in the non-rotating frame and does not require sensors installed on the rotating frame that requires transfer of data over a rotating interface.

4. APPLICATION OF METHODOLOGY TO A CANADIAN HELICOPTER

This dynamic parameter estimation methodology has also been applied to the analysis of multiple LCO events occurred in the Canadian CH-149 Cormorant helicopter fleet. The Cormorant is a medium sized helicopter developed by Agusta-Westland. The Canadian Cormorant helicopter is equipped with a vibration monitor and recording system, known as CVMRADS, in which eight accelerometers are installed in the stationary frame of the vehicle to measure vibration levels during flight. Specifically two accelerometers are installed in the Fore/Aft and Lateral directions of the tail rotor gearbox to monitor the significant vibration incurred by the LCO of the teetering tail rotor system.

Multiple LCO events have been recorded on the Canadian CH-149 Cormorant helicopters equipped with the Teetering Tail Rotor (TTR) system, and the aeroelastic parameter identification methodology presented in this paper has been applied to analyze the recorded vibration data during the LCO events to extract the aeroelastic parameters of the critical rotating frame tail rotor mode. One LCO event was recorded on the vehicle CH-149913 in which three minor LCO incidents were reported within 4 minutes. The pilot managed to perform correctional operations to ensure flight safety during the search and rescue mission. The time trace and aeroelastic parameters of the regressive mode of the first LCO incident are shown in Figure 3. High vibration level up to 2.0g was observed within the regressive band of 10-15 Hz, and significant vibration was also identified within the progressive band. However, since there was no sensor installed in the rotating frame, the aeroelastic parameters of the critical tail rotor mode were estimated based on the stationary frame information in order to assess the impact to the integrity of the teetering tail rotor structure with confidence.

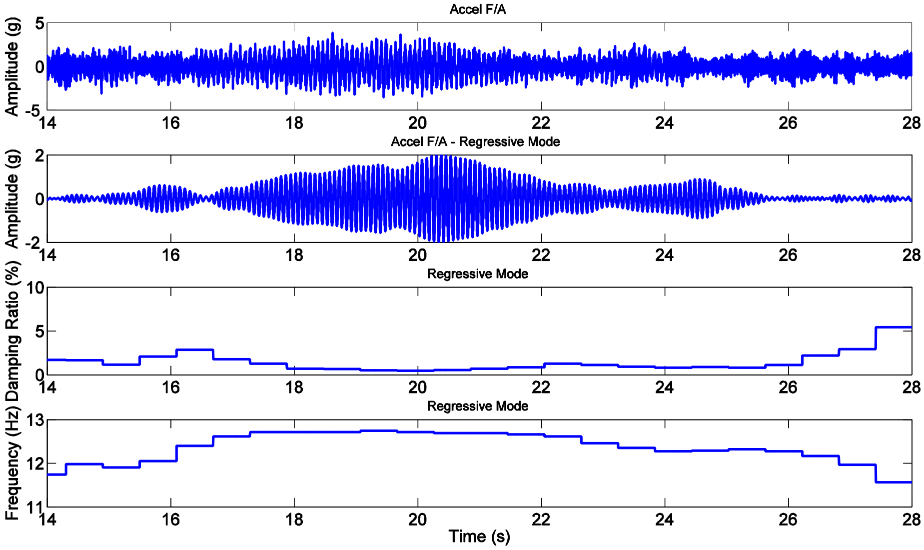


Figure 3. LCO event on the Cormorant CH-149913

The aeroelastic parameters of the regressive and progressive modes have been identified based on the vibration data measured in the Fore/Aft direction of the tail rotor gearbox. The aeroelastic parameters of the critical rotating frame mode were estimated using the center frequency scaling relationship, and the results are shown in Figure 4. Both the damping ratio and frequency traces showed variations in relation to changes in vibration levels, and retained similar trends as the regressive mode as would be expected for an aeroelastic instability event. The lowest damping ratio was found to be 0.18% in the rotating frame and was related to the 19th second of the shown time trace while the corresponding frequency was 28.9Hz.

The aeroelastic parameters of the critical tail rotor mode during the other two LCO incidents have also been identified using the same methodology. The results were then compared with two other LCO events, one which occurred on the same vehicle in another flight mission and the other which occurred on the same version vehicle CH-149910. All aeroelastic parameters were identified based on the vibration data measured by the CVMRADS exclusively in the stationary frame. The damping ratio parameters are listed in

Table **2** for comparison. Since these aeroelastic parameters were estimated for the critical tail rotor mode in similar LCO events during flight conditions, they would enable establishing the tail rotor stability diagram and understanding the margins in the aeroelastic design of the Cormorant teetering tail rotor system more accurately. Moreover, the impact on structural integrity of the Cormorant teetering tail rotor structures in these LCO events could also be quantified with confidence and fidelity.

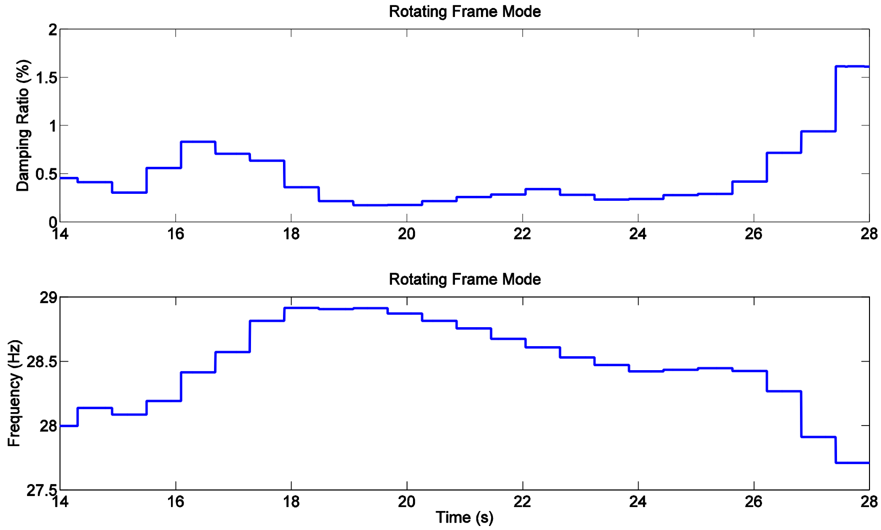


Figure 4. Modal parameters estimated for the half hub mode

Table 2: Damping Ratio Parameters Identified on Cormorant LCO Events

LCO	CH149913 LCO EVENT A			CH149913 LCO EVENT B			CH149910 LCO EVENT		
	Stationary		Rotary	Stationary		Rotary	Stationary		Rotary
	Regressiv	Progressive	Rotor	Regressiv	Progressive	Rotor	Regressiv	Progressive	Half Hub
1	0.94%	0.26%	0.41%	0.79%	0.18%	0.32%	0.85%	0.28%	0.41%
2	1.00%	0.22%	0.39%	0.67%	0.20%	0.31%			
3	0.73%	0.29%	0.38%	1.06%	0.25%	0.43%			
4	0.91%	0.24%	0.38%						
5	0.99%	0.22%	0.39%						
6	1.14%	0.24%	0.43%						
7	1.22%	0.30%	0.50%						

Multiple representative LCO events on Cormorant vehicles have verified that, using the center frequency scaling factor relationship, the aeroelastic parameters of the critical tail rotor mode, namely the modal frequency and damping ratio, can be reliably estimated based on the aeroelastic parameters of the regressive and progressive modes which can be identified from vibration data measured in the stationary frame. As long as the measured vibration data in the stationary frame provides reasonable signal to noise ratio to ensure reliable identification of the regressive and progressive modes, the aeroelastic parameters of the critical rotating frame mode can be estimated without the need for sensors to be installed in the rotating frame. This provided a simple yet reliable approach in the evaluation of aeroelastic features for the helicopter tail rotor system during LCO events based on vibration data measured exclusively in the stationary frame.

5. CONCLUSION

This paper presented a center frequency scaling factor relationship that enables the correlation of aeroelastic parameters of the helicopter tail rotor critical mode and the derived regressive and progressive modes in the stationary frame of a helicopter tail rotor system during LCO events. The application of this relationship was validated through multiple LCO events occurred on the helicopter tail rotor system. Extensive analysis revealed that the regressive and progressive modes were not independent structural modes, but derived as paired modes due to the modulation of the tail rotor mode with the 1/rev tail rotor rotating speed. This provides a reliable methodology and tool to estimate the dynamic vibration parameters of a rotating frame structure such as aeroelastic parameters, without the need to install additional sensor or signal transmission path in the rotating frame structures.

It is also important to note that this relationship is not application specific to helicopter tail rotor vibration events, and it can be applied to the analysis and monitoring of other dynamic rotating events in order to estimate vibration parameters of the rotating structures using vibration data measured exclusively from the stationary frame structure which would simplify the system configuration greatly.

ACKNOWLEDGMENTS

The project is supported by the Department of National Defence Canada.

REFERENCES

1. Guillaume, P., Verboven, P., and Vanlanduit, S., “Freqeuncy-domain maximum likelihood identification of modal parameters with confidence intervals”, Proceedings of ISMA 23, the International Conference on Noise and Vibration Engineering, Leuvenm Belgium, Sept 16-18, 1998.
2. Peeters, B., Auweraer, H.V.D., Guilaume, P., and Leuridan, J., “The PolyMAX frequency-domain method: a new standard for modal parameter estimation”, *Shock and Vibration*, Vol. 11, 2004, pp 395-409.
3. Maia, N.M. et al. Experimental Modal Analysis, Chichester: John Wiley & Sons, pp.468.
4. Maia, S., He, L. and Urgueira S. T., Theoretical and Experimental Modal Analysis, Research Studies Press, Baldock, Hertfordshire, England, 1996.
5. Mehra, R.K., Mahmood S. and Waissman R., “Identification of aircraft and rotorcraft aeroelastic modes using state space system identification”, Proceedings of the 4th IEEE Conference on Control Applications, Sept 28-29,1995, pp. 432–437.
6. Juang, J.-N., and Pappa, R. S., “An eigensystem realization algorithm for modal parameter identification and model reduction”, *Journal of Guidance, Control, and Dynamics*, Vol. 8, No. 5, 1985, pp. 620-627.
7. Peeters, B. and Rodeck G.D., “Reference-based stochastic subspace identification for output-only modal analysis”, *Mechanical Systems and Signal Processing*, Vol. 13, No. 6, 1999, pp. 855-878.

8. Mucheroni, M.F., and Cardoso, A., “Output-only Structural Identification of random Vibrating Systems”, *Journal of Brazil Society of Mechanical Science and Engineering*, Vol. 28, No. 1, 2006, pp.99-104.