Rotor Blade Vibration Measurement on Aero Gas Turbine Engines

T. Devi Priya, Sunil Kumar, Devendra Pratap, S. Shylaja, T. N. Satish, and A. N. Vishwanatha Rao

Abstract Rotor blade vibration in turbomachinery has been a major cause of failure due to HCF, often resulting in catastrophic damage. The primary aeromechanical design concerns are blade flutter and forced vibration that need to be quantified. The severity of blade vibratory response is almost impossible to predict using theoretical tools as it depends on the strength of excitation. Hence in order to evaluate the HCF characteristics of rotating blades, aero industry depends on measurements for actual vibratory response during engine tests. Various methods are used for measurement of rotor blade vibration. Conventionally strain gauges are extensively used for characterizing vibratory signatures of rotating blades. However, the strain gauges have their own limitations posed by operating temperatures and high-end technology is required to transmit signal from rotating components. Hence only a few blades in a rotor can be instrumented resulting in limited data capture. This paper presents a non-contact type of measurement technique using blade tip timing to capture vibratory signatures of all the blades of the rotor stage. This method is used to characterize monitor rotor blade vibrations of Low-Pressure Compressor and Low-Pressure Turbine of a developmental gas turbine engine. It has provided valuable data with respect to incipient damages, preventing catastrophic failure.

Keywords HCF · Blade resonance · Flutter

1 Introduction

Since the advent of gas turbines, and their applications in various industrial sectors, blade failures have proven to be a major cause of breakdown, often resulting in catastrophic damage [1]. The most common types of vibration problems that concern the designers are resonant vibration occurring at an integral order and flutter, an aeroelastic instability occurring generally as a non-integral order vibration, having

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the potential to escalate, into larger stresses thereby may lead to structural failure of the blades.

Measurement of blade stresses by conventional method involves instrumenting selected set of blades with strain gauge. High-speed slip ring or telemetry unit housed inside the engine is required for data transfer from rotating strain gages to stationary data acquisition systems. As robust case mounted sensors are used by NSMS system, it can perform long term health monitoring tests with minimal probe maintenance as against the conventional strain gauges which have a high mortality rate. The more innovative, Non-intrusive Stress Measurement System using blade tip timing method uses time-of-arrival to characterize and monitor the blade vibratory response of all blades. The present study elaborates the usage of NSMS system for monitoring LP Turbine and Fan blade vibration in a developmental aero engine program.

2 Blade Tip Timing Technique

BTT is a non-intrusive technique for characterizing vibrations of bladed systems in rotating turbomachinery [2–5]. Figure 1 shows the schematic of BTT technique. The system consists of tip timing sensors, signal conditioners, PXI based data acquisition, and monitoring system to acquire the response of every single blade on a rotor stage.

The case mounted sensors sense every blade pass to give an analog signal. The sensor outputs are suitably conditioned and processed to generate TTL pulse for each blade pass using BVSI unit. The generated TTL pulse is then timed accurately using high speed (80 MHz) counter/timer hardware. This data is then used in conjunction with a 1/rev sensor mounted on the shaft of the engine to compute blade time-of-arrival information for each blade which is a measure of blade tip deflection.

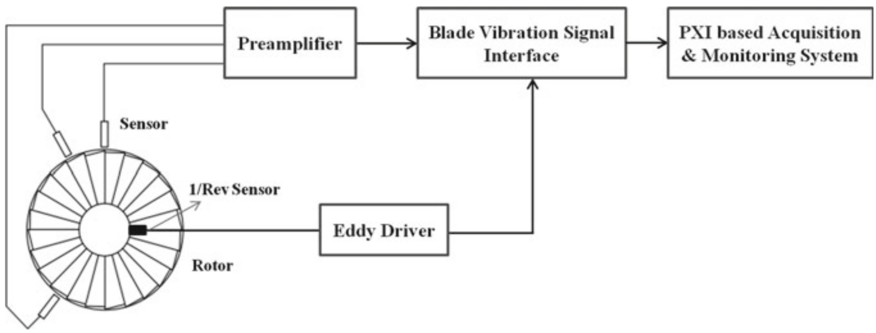

Fig. 1 Schematic of BTT technique

3 Computation of Blade Tip Deflection Using TOA

The calculated time-of-arrival defines the actual position of a blade. In case of a uniformly spaced rotor with vibrations, a difference between the calculated and measured TOA is reported as a blade lag, either positive or negative. However, a uniformly spaced rotor with no vibrations will always have the same TOA, assuming the static deformation to be constant [6, 7], Fig. 2.

The TOA of each blade is converted to deflections using the following equation

$$\text{Blade Tip Deflection} = \text{Vt} = 2\pi \text{r}\left(\frac{\Delta \text{t}}{\text{T}}\right)$$

where

Rotational Velocity (V)—revolutions per minute

Radius to blade tip (r)—inches

Δt = calculated TOA—measured TOA

T—time for one revolution of all the blades

From the blade tip deflections, stress levels can be calculated using stress to deflection ratios obtained from FE models.

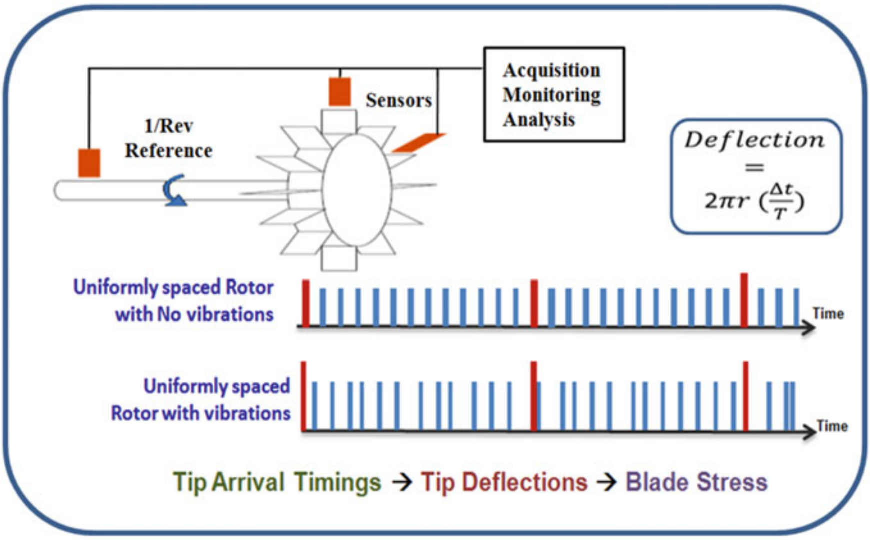

Fig. 2 Computation of blade tip deflection

4 Instrumentation

NSMS instrumentation consists of a set of case mounted sensors that determine the time-of-arrival of a blade tip at a particular case location. This characterizes the entire rotor stage, including the disk. Various types of sensors such as passive eddy current sensors, optical sensors, capacitive sensors, and magnetic sensors can be used to produce a signal for each blade pass [8–10]. The tip timing method utilizes these signals to measure the arrival times of the rotating blades with respect to the non-vibrating reference signal, to compute the blade vibrations for every revolution. However in this method, knowledge about the existing vibration modes is a prerequisite.

Sensors selection and placement on the rotor circumference is critical in configuring the NSMS system for blade vibration during resonance. This location is decided based upon the blade modes of interest and expected engine order crossovers in the operating regime [4]. Figure 3 shows the angular positions of the sensors as implemented on Fan, Bearing housing (1/rev), and LPT. Measurements are made on the blade trailing edge based on the max deflection pattern obtained from finite element analysis and site availability on the blade tip. Figure 4a shows photograph of a once

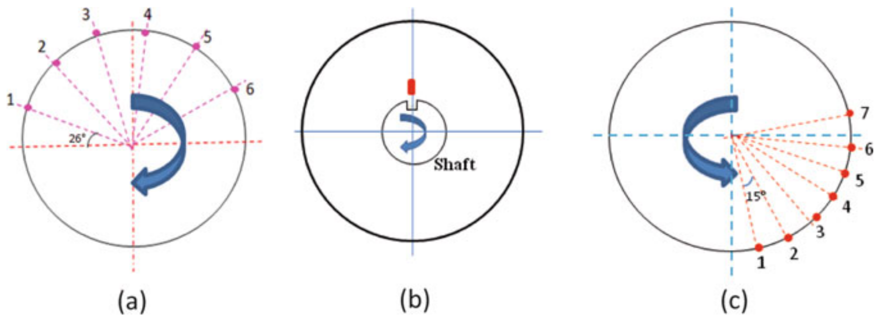

Fig. 3 **a** Circumferential sensor location on Fan casing **b** 1/Rev sensor in bearing housing **c** Circumferential sensor location on Turbine casing

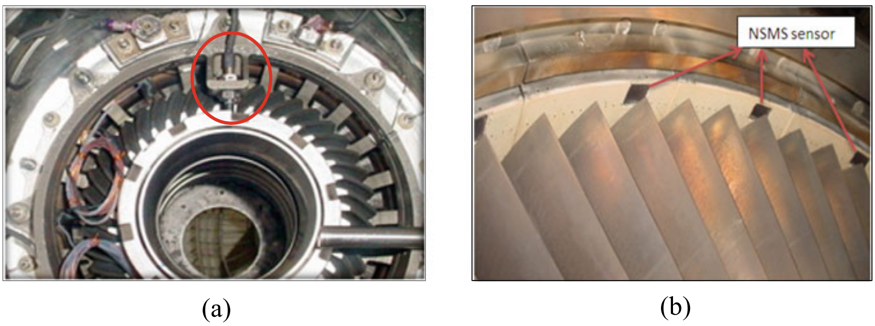

Fig. 4 **a** 1/Rev sensor installed on engine **b** NSMS sensor installed on the Turbine casing

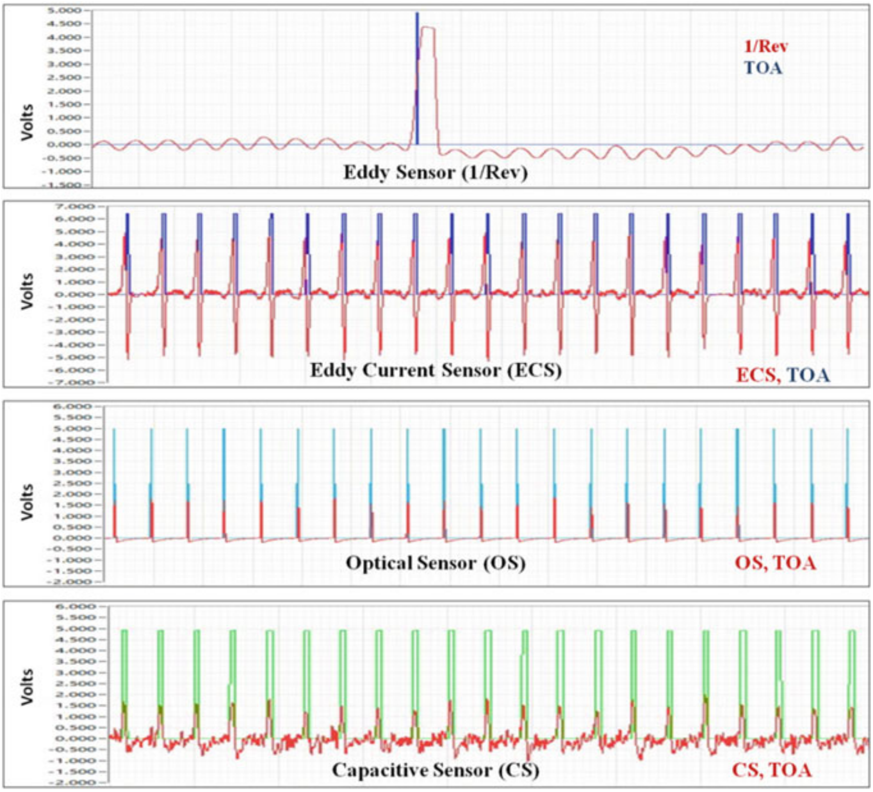

Fig. 5 Sensor output and its TOA from various types of sensors

per revolution (reference) sensor mounted in the bearing housing. Figure 4b shows photograph of NSMS sensors installed on the turbine casing facing the tip trailing edge of the blade. The sensor output and TOA pulse captured for one revolution for various types of sensors are given in Fig. 5.

5 Tip Timing Data Analysis

During engine testing rotor blades usually undergo two kinds of blade vibration—Forced vibration and Flutter. Forced vibrations are due to the stationary disturbances that could be upstream and downstream vanes or inlet flow distortion. Synchronous resonances are assembly modes that are excited at integer multiples of the rotational speed. This multiple is referred to as the Engine Order (EO) of excitation. At a given speed, the phase of the response remains fixed relative to a stationary (and arbitrary) datum. Asynchronous vibration mainly occurs because of aerodynamic instabilities and hence both the resonant frequency and the phase of the response can be arbitrary. NSMS system has different algorithms to process synchronous and asynchronous vibration. It uses SDOF curve fit for analyzing synchronous vibration and spectral analysis for asynchronous vibration. SDOF curve is used to extract resonance characteristic parameters—amplitude, frequency, phase, and q-factor [4, 9].

6 Engine Test Results and Case Studies

6a Case Study-1: Low-Pressure Turbine Blade Failure Avoidance during Engine Testing

In the case of synchronous vibrations, the blade frequency of vibration is an integer multiple of the rotational frequency of the assembly. The blade tips have nominally the same displacement every time they pass the probes if the assembly is running at a constant speed. Hence, the displacement data are essentially repeated at each revolution and the analysis of the data becomes a lot more difficult.

The synchronous analysis method, therefore, needs an RPM sweep across the expected critical speed where the displacement data will vary for each revolution. When the computed TOA data for every revolution is plotted against engine RPM, this data forms the resonance Frequency Response Function (FRF). The vibratory response parameters—resonance frequency, response amplitude, resonance factor, and phase are then computed, through an SDOF curve fit approach. The process characterizes the resonant response of each blade in the disk. The critical resonance crossovers in the operating regime are predicted using FEM and analytical Campbell diagram generated is shown in Fig. 6.

Damage in rotor blades, including cracks, tend to shift the blade's resonant frequencies. Blade resonances have thus envisioned as damage indicators [11–13]. In this case study, the low-pressure turbine stage of a developmental aero engine is instrumented with high-temperature eddy current and optical sensors. The sensors are placed circumferentially on the turbine casing as shown in Fig. 4c to capture third and fourth engine order (3EO and 4EO) resonances for the first blade bending mode (1F). During engine tests blade vibratory amplitude and resonance frequency of all the blades are monitored. Post-test analysis is carried out to extract vibratory response parameters. The SDOF curve fit for LPT blade-12 in healthy condition during 3EO resonance crossover from all the sensors is shown in Fig. 7a. During a particular Engine test, it was observed that blade-12 had a drop in its 3EO resonance frequency. Suspecting a propagating crack in the particular blade, the engine operator was cautioned to abort the engine test. Post synchronous analysis (SDOF) indicated four percent drop in 3EO frequency accompanied by reduction in resonant amplitude, as shown in Fig. 7b. The 3EO frequency scatter of all LPT blades for the normal and the aborted engine tests is shown in Fig. 8. The test Campbell diagram of the suspected blade-12 is plotted in Fig. 9. Later the engine was removed for detailed

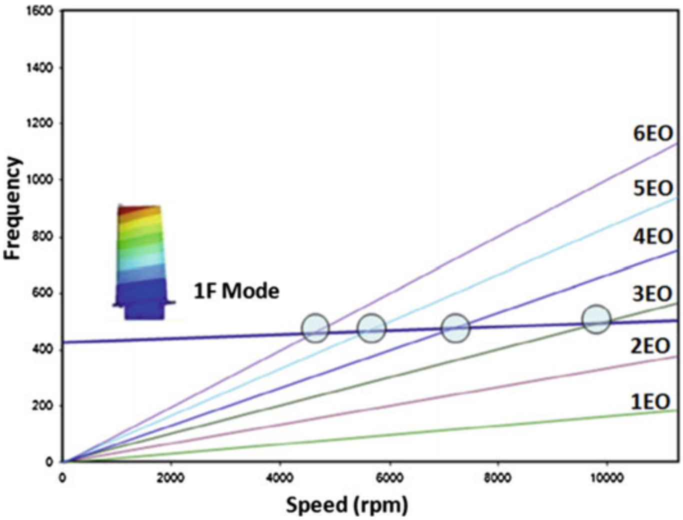

Fig. 6 Analytical Campbell diagram

inspection. The suspected blade was subjected to Fluorescent Penetrant Inspection. FPI confirmed a major crack in the suspected blade. Thus a major catastrophic engine failure was averted.

6b **Case Study-2: Flutter Detection in Fan Blades**

In the case of asynchronous vibrations, blades vibrate at frequencies that are not multiples of Engine order [9, 13–15]. The traveling wave analysis is used for non-synchronous responses, such as flutter, where the blades vibrate at same frequency and constant phase difference. The best way to analyze flutter data is to process it as a coherent vibration where each blade is treated as a sampling of this waveform. Nodal Diameter (ND) pattern of the response can be determined by comparing the measured phase of the cross-spectrum between two sensors and comparing it to the circumferential angle between sensors. As blade vibrations are measured in the stationary frame of reference, true blade frequency in the rotating frame is then computed using the following equation

$$f_{observed} = f_{true} \pm ND\, f_{shaft}$$

where ND is the number of nodal diameters in the vibration pattern.

In this case study, Fan first stage rotor of a developmental aero engine is instrumented with eddy current, capacitive and optical sensors. The sensors are placed circumferentially on the fan casing (Fig. 4a) to capture both integral and non-integral engine order resonances in the operating regime. During one of Engine test, high asynchronous vibratory response was observed at 86 % dwell. Since the response amplitude was exceeding the limits, warning was provided to abort the test. Detailed

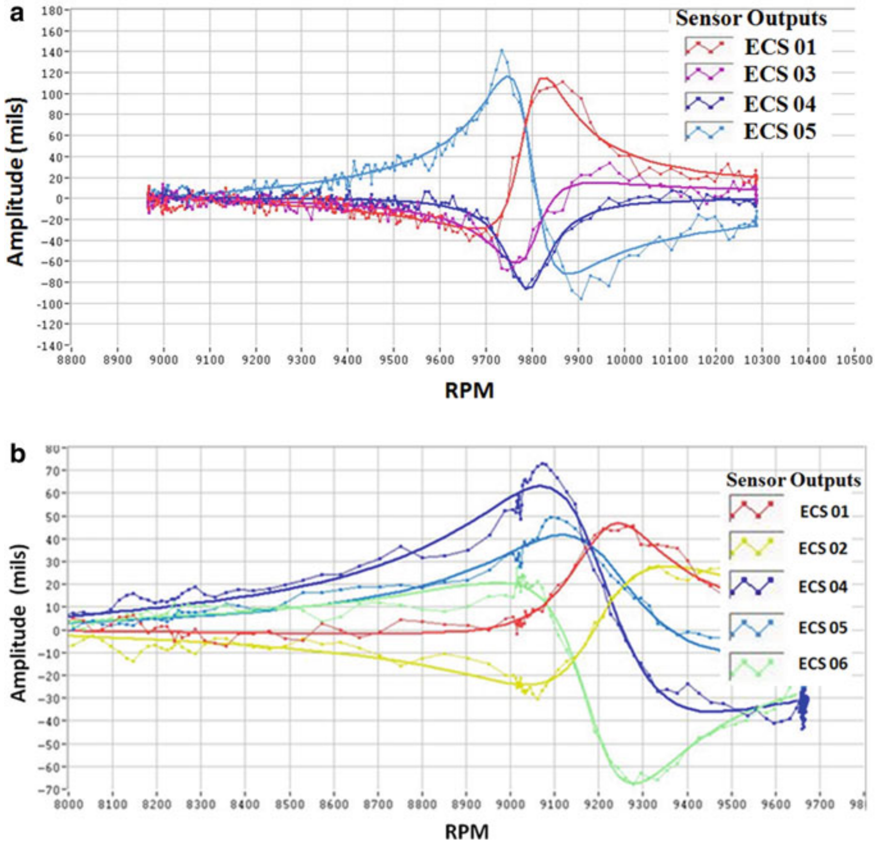

Fig. 7 **a** 3EO SDOF curve fit for blade-12 in healthy condition **b** 3EO SDOF curve fit of blade-12 indicating 4 % drop in frequency

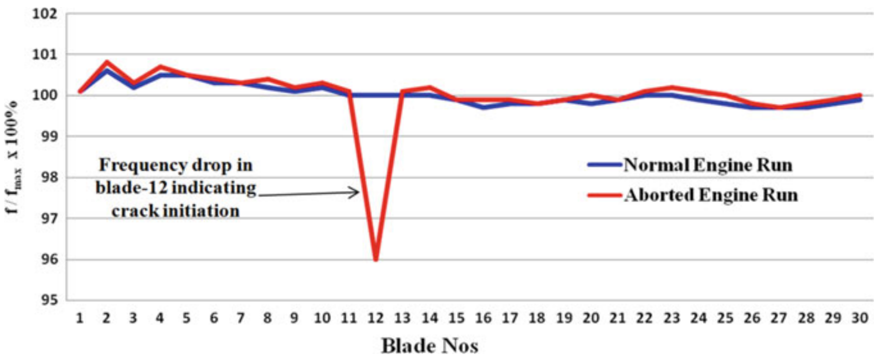

Fig. 8 3EO frequency scatter of LPT blades during normal and aborted engine runs

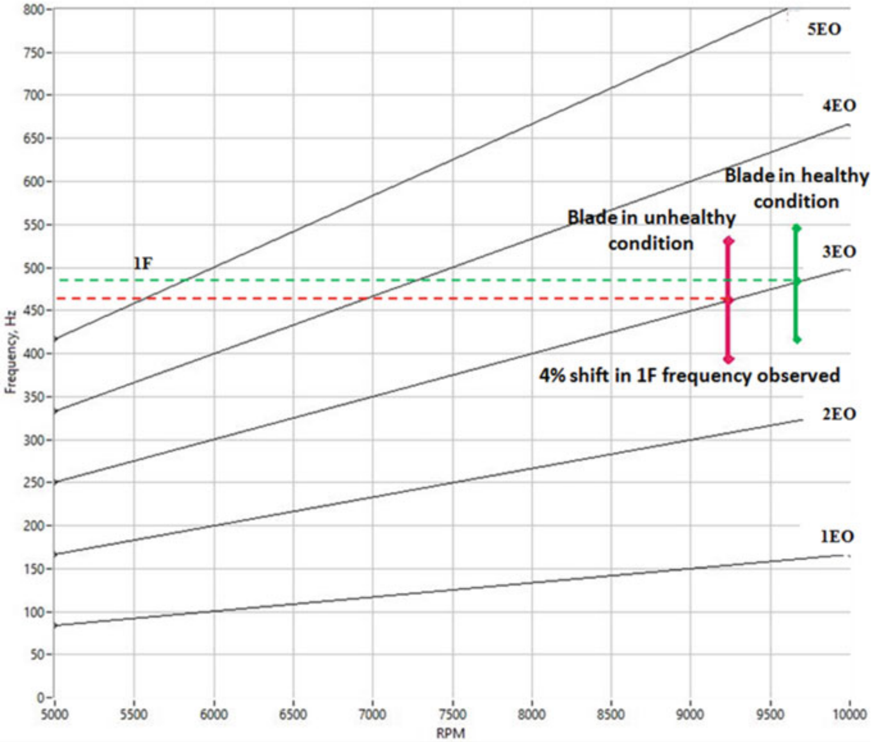

Fig. 9 Test Campbell diagram of blade-12

offline analysis was carried out to investigate the cause of high amplitudes. Test Campbell diagram (Fig. 10) indicated that blades vibrated at 1.8EO, dominant with 2ND. The investigation revealed that flutter was the cause for high blade vibration.

7 Conclusion

The ability of NSMS system for monitoring synchronous and asynchronous vibration of rotating blades has been demonstrated with two case studies. It has provided valuable data with respect to incipient damages, preventing catastrophic failures.

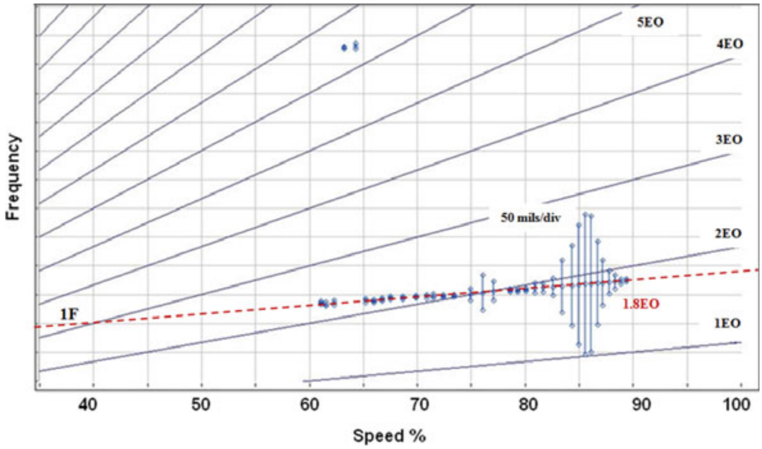

Fig. 10 Test Campbell diagram during Fan1R flutter

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