Vibration Representation in Time and Phase Domains, Applications to Aircraft Engines

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Abstract

While in operation, aircraft engines may be subjected to various severe mechanical events such as bird ingestion, blade separation, ice accretion, shaft unbalance, compressor stall or rotor-stator interaction. During the development of a new engine application, such phenomena are simulated in test cells in order to make sure that the engine will still operate safely. During such tests, accelerometers and strain gages are mounted on the engine cases and near the shaft bearings in order to measure loads and vibrations and in order to understand the engine behaviour. The engine dynamic behaviour during those phenomena may be fleeting or sustained, cyclic or asynchronous, transient or stationary. Usual analysis are performed in various domains such as time, frequencies and orders of a rotating shaft speed, depending on the nature of the vibration behaviour.

This paper describes a new kind of vibrations representation that considerably facilitate the interpretation of fleeting or sustained events when both time and phase location of a shaft are meaningful. In a first section of the paper, the representation is described with a simple simulation of a rotating shaft operating with variable angular speed. In a second section, the representation is applied on a real aircraft engine during tests with various engine behaviours. The last section presents a simulation of those different behaviours with a simple lumped-mass model.

1 Introduction

Aircraft engines may be subjected to various severe mechanical events such as bird ingestions, blade separation, ice accretion, shaft unbalance, compressor stall or rotor-stator interaction [1].

During the development of a new engine application, such phenomena are simulated in test cells in order to make sure that the engine will still operate safely.

Those phenomena may be transient or stationary, synchronous, almost synchronous, or not correlated with the rotating speed of a shaft. They may be caused by internal activity of the engine or by external aggression. In order to better understand the behaviour of the engine during those tests, the engine is equipped with acceleration or displacement sensors, strain gauges, tachometers, temperature and pressure sensors and high speed cameras. Those measurements are recorded with a sampling frequency in the range from 10 Hz to 100 kHz, depending on the sensors capabilities and on the frequency content that is expected to happen during the test.

The measurements are then analysed with different kinds of data processing tools in order to extract from the noise the relevant information that will facilitate the understanding of the phenomena. According to the type of events, several kinds of data analysis are appropriate. Frequency analysis, order analysis [2], wavelet analysis and image processing are standard tools that may be very helpful. Another very popular tool is simply the analysis of the time history of different measurements when they are synchronized. Such analyses may be performed after some data processing such as non-causal filtering in order to enhance the information hidden in the signal. Time history analysis can reveal correlation or causality between phenomena.

In this paper we present a new representation of time history where we add the dimension of angular position of a shaft in the display of the signals.

In a first section, the representation is described with a simple simulation of a rotating shaft operating with variable angular speed.

In a second section, the representation is applied on a real aircraft engine during tests with various engine behaviours. The relevance of the new representation compared to more usual representation is discussed.

The last section presents a simulation of those different behaviours with a simple model.

For sake of confidentiality, plots units are normalized. Also, experimental and model parameters are not shared throughout the paper.

2 Description of the time/phase representation with a simple simulation

In order to explain the transformation of a standard time history representation to a time/phase domain representation, we will use a simple simulation of a vibration synchronous with a shaft rotating speed. A vibration signal was simulated with the following hypotheses:

- A rotating speed N of the shaft that decreases linearly, and with an inversion of the direction of rotation,
- A vibration signal that is synchronous with the rotating speed,
- The amplitude of the vibration that is proportional to the square of the rotating speed.

A standard time history representation of this simulation is illustrated in figure 1. As can be seen on figure 1(b), the sign of the rotating speed is meaningful for the representation of the shaft angular position. A convention shall be used for the sign of the rotating speed, for instance it could be positive when the shaft rotates in the clockwise direction in the ‘forward looking aft position‘.

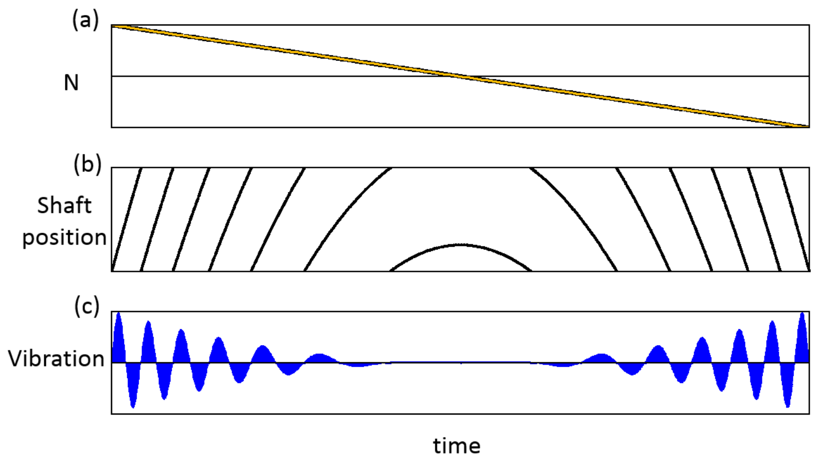

Figure 1: Standard time history representation with a simple simulation. Time history of the rotating speed N of a shaft (a), time history of the shaft angular position (b), and time history of a simulated vibration signal (c).

In a standard time history representation, the amplitude of the vibrations is plotted on the y-axis.

The representation in the time/phase domain of the simulated signal is shown in figure 2(a).

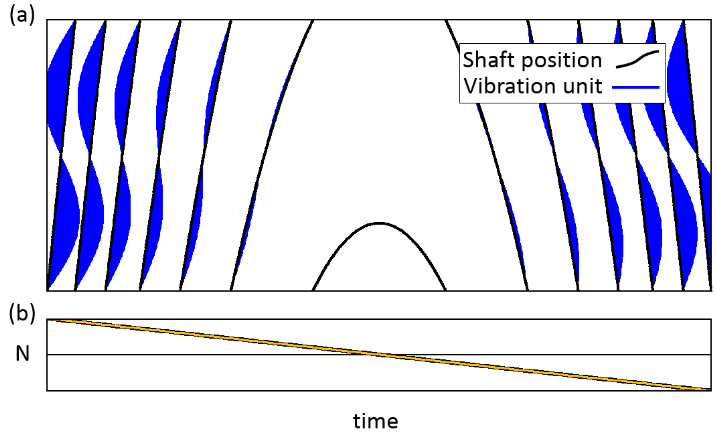

Figure 2: Representation in the time/phase domain (a) and time history of the shaft rotating speed (b).

This representation is composed of two signals:

- A plot of the time history of the shaft angular position,
- A plot of the vibration amplitude around the shaft angular position plot.

In such representation, the vibration is plotted in the direction of the x-axis. The zeros of the vibration amplitude are located on the curve of the shaft angular position.

A convention for the sign of the amplitude must be applied. As illustrated in figures 1 and 2, the convention used in this paper is to plot the positive values at the right of the shaft angular position, which is a natural convention. Another convention must be applied for the scale of the vibrations amplitude since the x-axis is also used for the representation of time. The scale of the vibration amplitude can be arbitrarily chosen, but it should be selected according to the range of amplitude and to the time length between two cycles for visual convenience.

Representation in the time/phase domain is therefore not a transformation of the signal, it is simply a different presentation of the time history of a signal. The aim of this kind of representation is to ease the identification and physical understanding of angular or temporal periodic phenomena present in the vibration signal.

In the next section, this representation will be applied to a variety of phenomena experienced by civil aircraft engines during engineering tests.

3 Application of the representation to several aircraft engine events

A first illustration in figure 3 is the installation of an oil unbalance. This event occurred while the rotating speed was almost stabilized as it can be seen on figure 3(c) and 3(d). The normalized rotating speed is plotted between 0 and max(N) while the detail is plotted between min(N) and max(N). In this case, the vibration signal is the displacement of the shaft in a given radial direction. This signal has been filtered with Vold-Kalman filters, described in [3], around 1 N and around 0.8 N.

The tracked signal around 1 N in figure 3(a) is representative of the displacement caused by a rigid unbalance of the shaft. This kind of unbalance is synchronous with the shaft. When the rotating speed is at steady state, the displacement caused by such unbalance also rotates synchronously with the shaft.

The tracked signal around 0.8 N in figure 3(b) is representative of an oil unbalance. Oil unbalance can occur when oil is present inside the shaft when a wave of oil is formed within. This wave causes an unbalance that is rotating in the direction of the shaft rotation but more slowly, hence the application of a filter around 0.8 N to track the displacement of the shaft caused by this type of unbalance. During this event, the rigid unbalance remained constant while the oil unbalance progressively increased in amplitude.

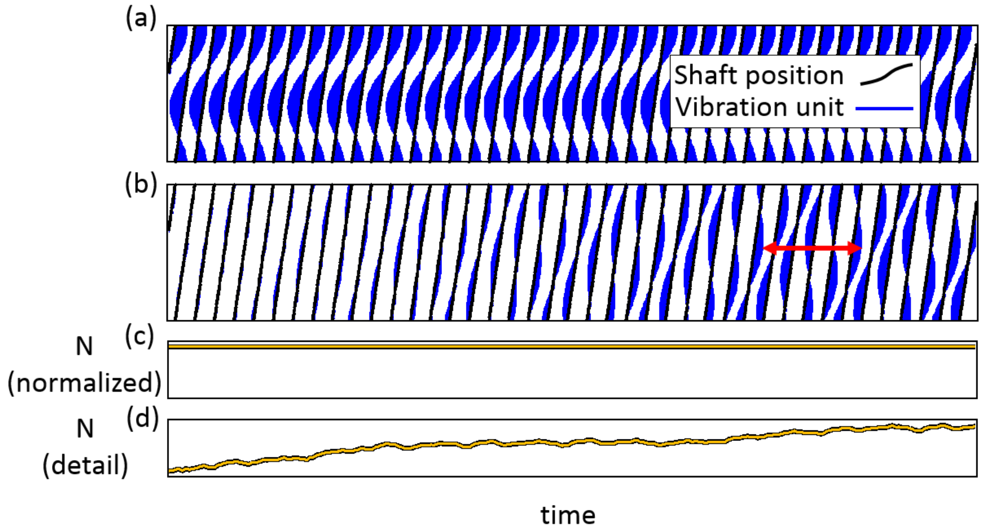

Figure 3: Application to a constant rigid unbalance and the progressive increase of an oil unbalance. Representation in the time/phase domain of the vibration amplitude tracked on the first order 1 N of the rotating speed (a) and of the vibration amplitude tracked around 0.8 N (b). Time history of the normalized rotating speed (c) and of the detail of the rotating speed (d). The red arrow shows that it takes 5 rotations of the shaft for the oil unbalance to be repetitive.

Another kind of test is ice accretion on the main shaft of aircraft engines. During ice accretion, several successive ice sheddings can occur. Those ice sheddings are fleeting events that change the unbalance of the shaft. Figure 4(a) shows an ice shedding and the high frequency content in the vibration during this event. Figure 4(b) is the vibration signal filtered around 1 N representative of the unbalance. In this case, the amplitude of the unbalance increases during the shedding. Figure 5 shows a different behaviour of an ice shedding. In this case, an unbalance was present prior to the shedding. After the shedding, the unbalance is higher and its angular location is at the opposite direction as can be seen in figure 5(b). Figure 4(d) and figure 5(d) show that the torsional mode of the shaft is excited by the sheddings.

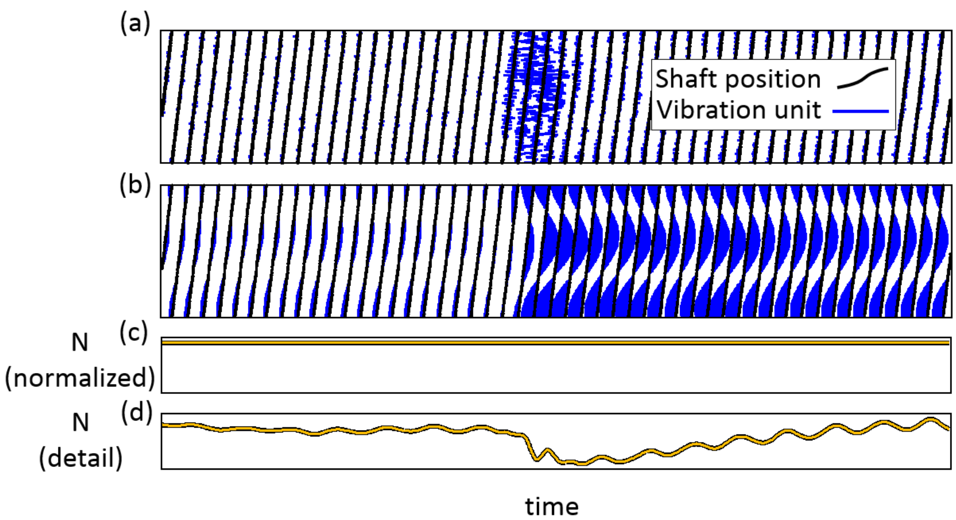

Figure 4: Application to ice shedding, fleeting event and sustained unbalance. Representation in the time/phase domain of the vibration amplitude (a) and of the vibration amplitude tracked around 1 N (b). Time history of the normalized rotating speed (c) and of the detail of the rotating speed (d). The unbalance increases in amplitude during the shedding while preserving its phase location.

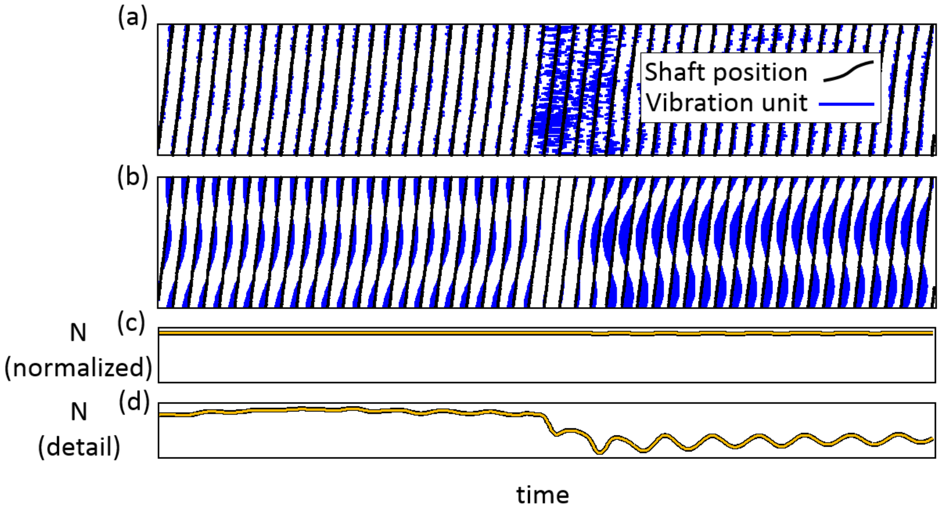

Figure 5: Application to ice shedding, fleeting event and change in unbalance amplitude and position. Representation in the time/phase domain of the vibration amplitude (a) and of the vibration amplitude tracked around 1 N (b). Time history of the normalized rotating speed (c) and of the detail of the rotating speed (d). The unbalance decreases and increases in amplitude during the shedding while its phase location is almost at the opposite direction.

The ingestion of several birds and the stall of a compressor are illustrated in figures 6 and 7. During those events, high frequency content appears but are not sustained. Time/phase representation is not really relevant in this cases where no obvious correlation of the frequency content and the phase location is observed.

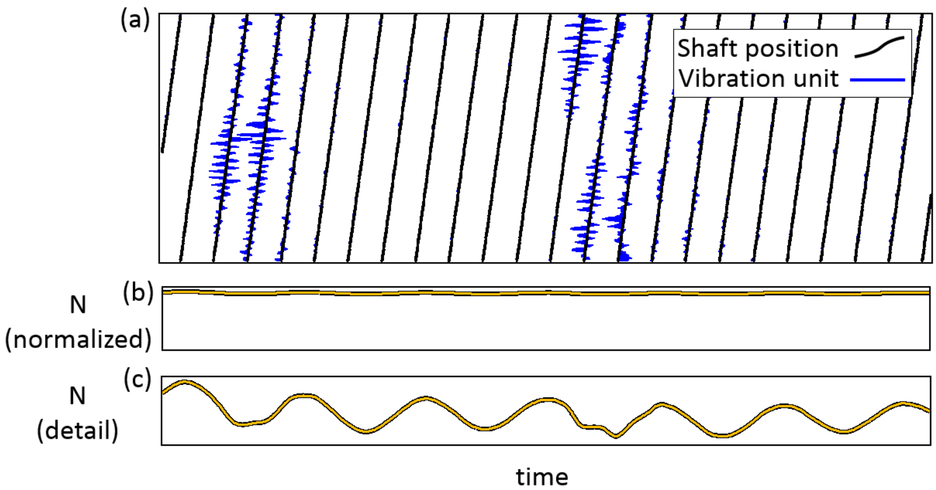

Figure 6: Application to the ingestions of several birds. Representation in the time/phase domain of the vibration amplitude of an accelerometer mounted on a stator close to the shaft (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c).

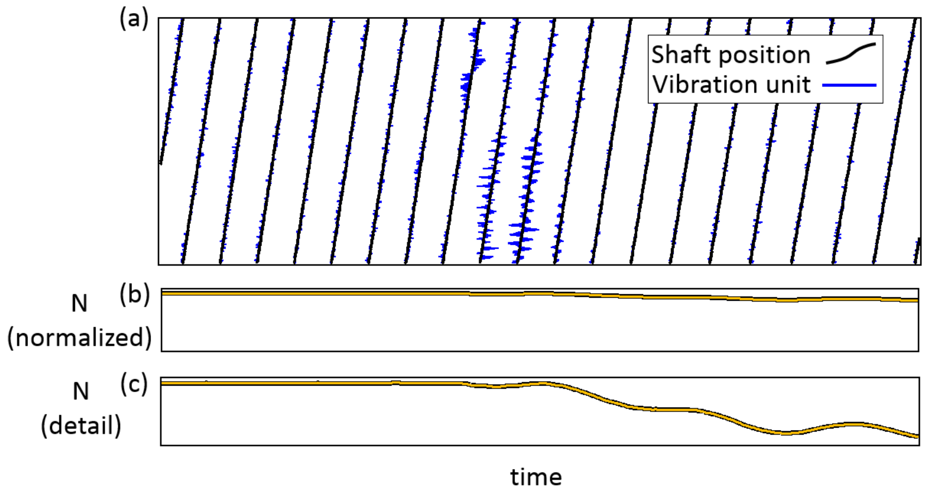

Figure 7: Application to a compressor stall. Representation in the time/phase domain of the vibration amplitude of an accelerometer mounted on a stator close to the shaft (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c).

Another severe event is the separation of a blade from the shaft. In this case, the unbalance can be huge and a solution is to change the dynamic response of the shaft in order to limit the loads in the engine and on the aircraft. During the deceleration of the shaft after a fan blade separation, the rotating speed crosses a rotor mode. Figure 8 shows the vibration representative of a load on a static bearing. During the crossing of the mode, the load increases and the phase delay between the load and the angular position of the shaft decreases.

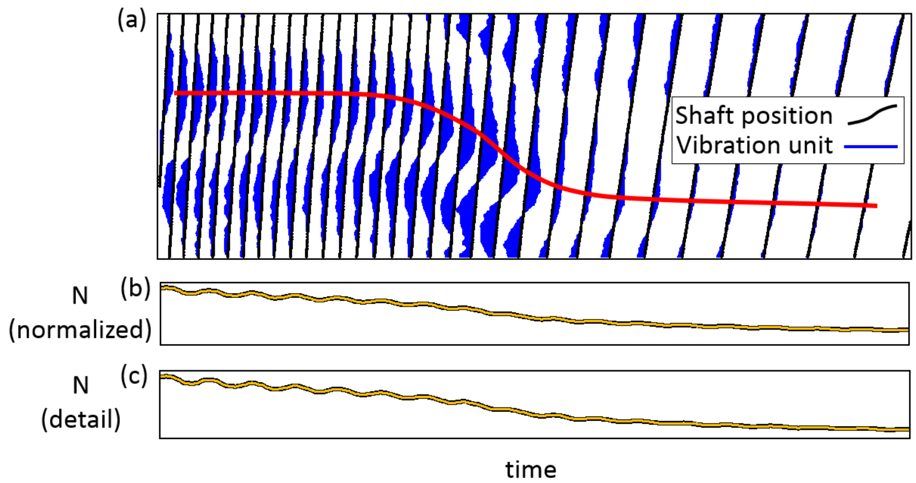

Figure 8: Application to the crossing of the rotating speed and a mode of the shaft. Representation in the time/phase domain of the vibration amplitude of a strain gauge mounted on a stator close to the shaft (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c). The red curve follows the maximal positive amplitude at each cycle.

The representation in the time/phase domain is particularly appropriate for the analysis of this type of event because the representation has an immediate physical sense that cannot be easily understood with other kinds of phase representation. For instance it is not necessary to understand if the convention for the phase between vibrations and a reference on the shaft is ‘phase lag’ or ‘phase lead’. In figure 7, it is obvious that the phase of the vibration is slowly accelerating, compared to the rotating speed of the shaft, during the crossing of the mode, and this is what is expected during a deceleration.

Figure 9 shows another behaviour for which the time/phase representation is particularly suitable. During this event, an interaction between the rotor and a static case occurred. The torsional mode of the shaft was excited, and the vibrations recorded on the static case shows that this interaction is characterized by an excitation of a sub-harmonic of the rotating speed. The time/phase representation allows to identify at a glance that the interaction occurs every three rotations of the shaft, and that the interactions occur when the shaft is approximately at the same angular position, meaning that the interactions between the rotor and the stator were very likely to appear repetitively in the same angular areas.

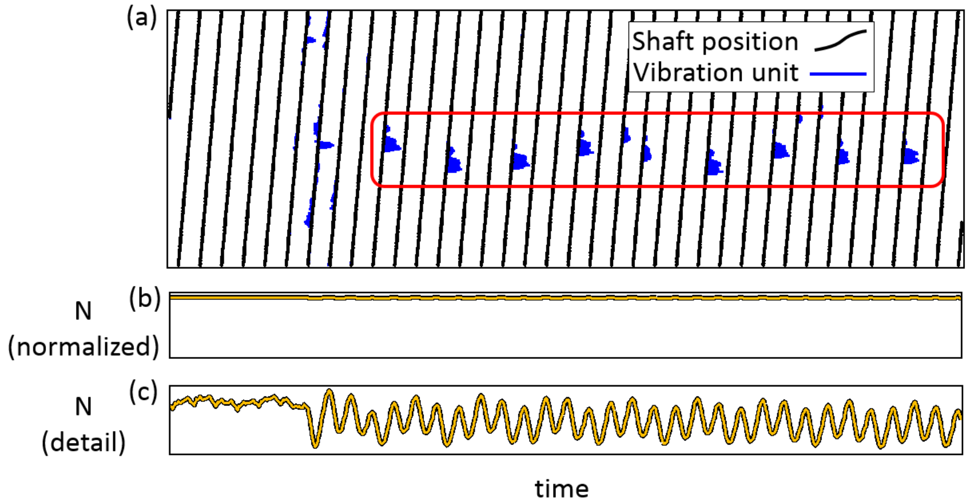

Figure 9: Repetitive shocks on a static case when a rotor interacts with a stator. Representation in the time/phase domain of the vibration amplitude of an accelerometer mounted on a case of the engine (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c).

4 Representation of several events with a simple model

Several events were simulated with a simple lumped-mass model [4]. Such simulations are typically used for the understanding of the dynamic behaviours of rotating shafts during the design of new aircraft engine types.

The lumped parameter model simulates the low speed shaft of an aircraft engine subjected to different external load conditions simulating the experimental cases shown on the previous section. Figure 10 shows a schema of the system which considers 3 degrees of freedom. The mass of the whole shaft is lumped to one rigid node resting on flexible supports with viscous damping.

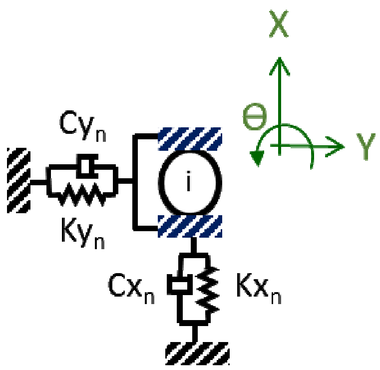

Figure 10: Lumped mass model Schema.

The general system of equations is:

$$[M].\{\ddot{X}\} + [C].\{\dot{X}\} + [K].\{X\} = \{F_{ext}(t)\} \tag{1}$$

Matrices M, C and K represent the mass, damping and stiffness of the system and vector X contains the generalized displacements of the node I on the x, y and Θ directions. The modelling approach is completely described in reference [4]. The resolution is performed in the angular domain as described in the given reference and the resolution is performed with Matlab's® ode15s solver.

Figure 11 shows the result of the measurements and of the simulation of the application of a rigid and constant unbalance and the application of a progressively increasing oil unbalance. The results from the simulation and from the measurements are very similar.

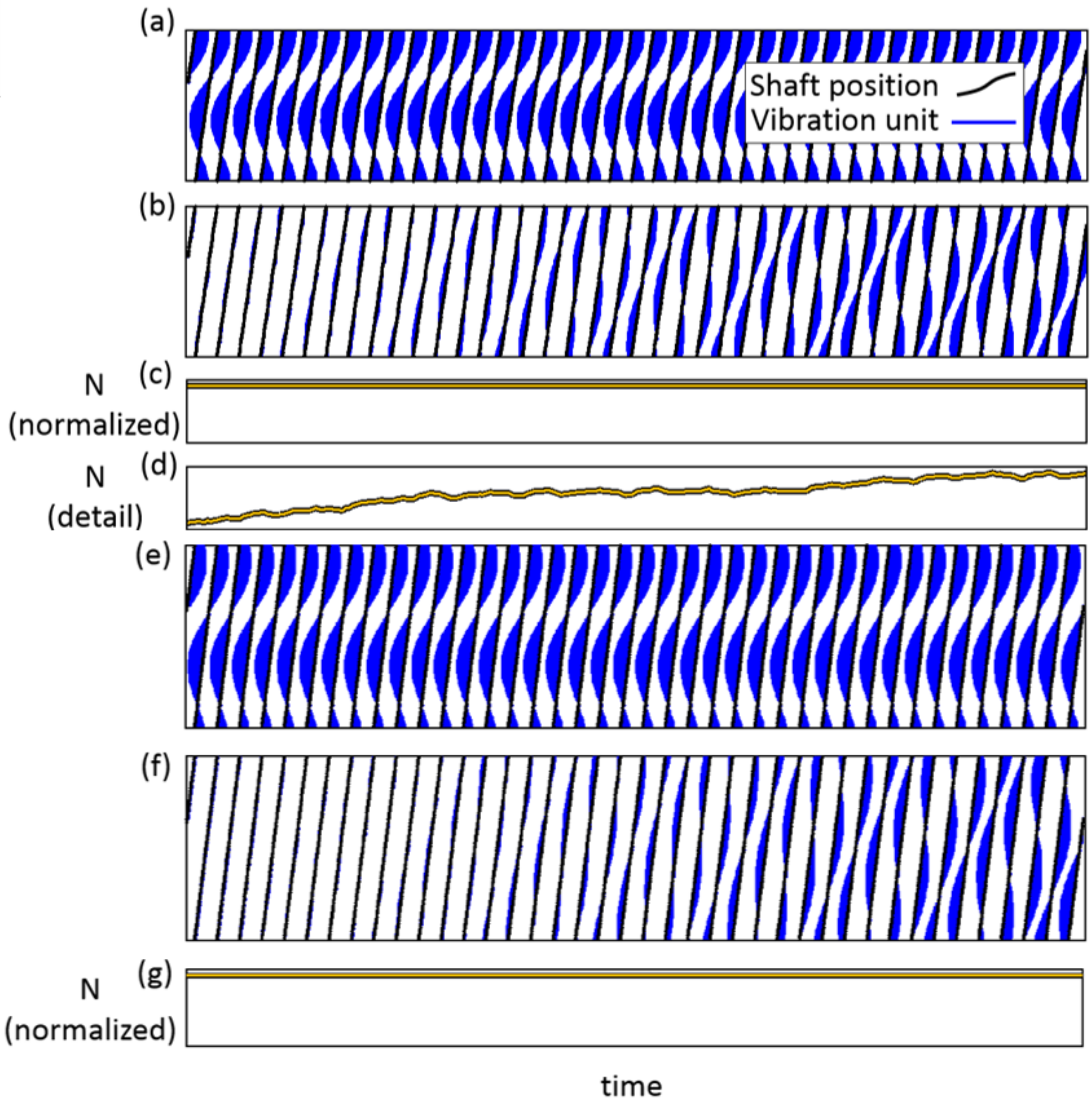

Figure 11: Application to a constant rigid unbalance and the progressive increase of an oil unbalance. Representation in the time/phase domain of the vibration amplitude tracked on the first order 1 N of the rotating speed (measurement (a), simulation (e)) and of the vibration amplitude tracked around 0.8 N (measurement (b), simulation (f)). Time history of the normalized rotating speed (measurement (c), simulation (g)) and of the detail of the rotating speed for the measurement (d).

Figure 12 shows the results of a simulation of the crossing of a rotating speed with a mode of the rotor. The model shows the changes in amplitude and phase that are similar to the changes observed during the tests in figure 8.

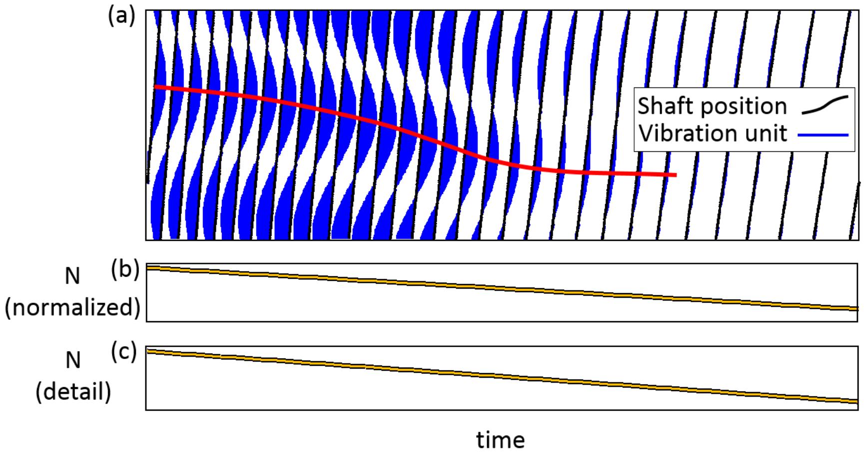

Figure 12: Simulation of the response to a crossing of the rotating speed and a mode of the shaft. Representation in the time/phase domain of the vibration amplitude of a strain gauge mounted on a stator close to the shaft (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c). The red curve follows the maximal positive amplitude at each cycle.

For the simulation of repetitive shocks between a rotor and a stator, the contact between the rotor and the stator has been simulated by a sudden change of the stiffness and damping in the vertical direction when the clearance is consumed due to unbalance as shown in Figure 13. The stator has been given a sinusoidal displacement law with a frequency close to a third of the rotating speed of the shaft.

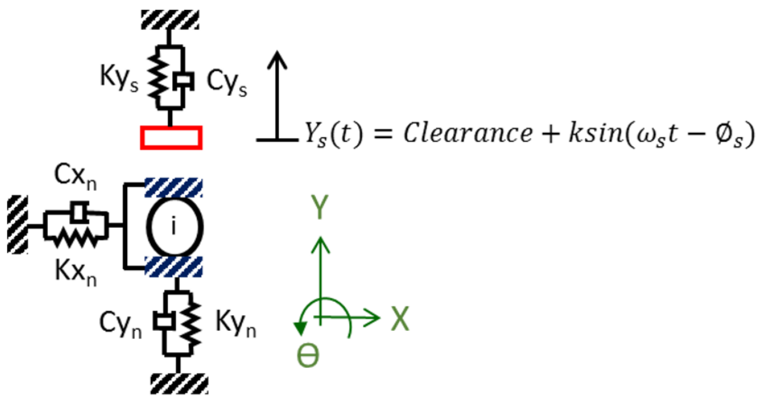

Figure 13: Rotor-stator contact model schema.

Figure 14 shows the results of the simulation of repetitive shocks between a rotor and a stator. The results are also similar to the records in figure 9.

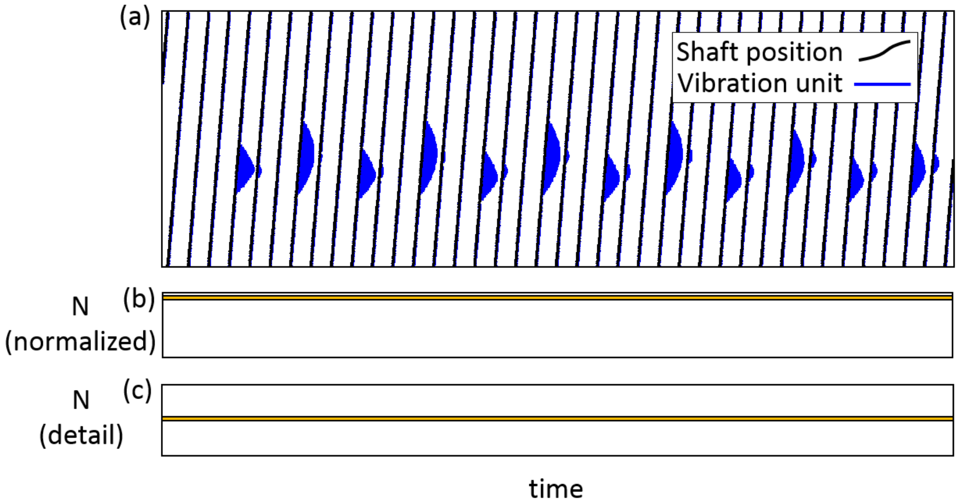

Figure 14: Simulation of the response to repetitive shocks. Representation in the time/phase domain of the vibration amplitude of an accelerometer mounted on a case of the engine (a). Time history of the normalized rotating speed (b) and of the detail of the rotating speed (c).

The results obtained with the very simple model and the comparison of those results with those obtained from tests are similar. The time/phase representation of both model and tests results facilitates this comparison.

The model can reproduce almost all dynamic behaviours observed during the tests with the time/phase representation. The only limitation is related to the impossibility to reproduce the torsional mode because there is only a single degree of freedom on the angle direction. Most influencing factors can be identified while changing the parameters of the model (mass, stiffness damping, external loads and rotating speed) without further expensive tests on real aircraft engines.

5 Conclusion

A new representation of vibration signals in the time/phase domain has been described. This representation has been applied on data recorded during several tests of aircraft engines, and on results obtained from a very simple model. The benefits of this representation are the following:

- The representation is a small change of the standard time history representation, it is therefore easy to become familiar with the new representation,
- The representation facilitates the search for correlations between the vibrations and the angular location of the shaft because the angular location is on the y-axis of the graphs,
- The time axis is preserved, correlations can be identified and causal analysis can be performed.

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