Angular vibration on-site measurements and application to torsional analysis on industrial cases

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Abstract

The measurement and analysis of torsional phenomena remains an uncommon and challenging task to perform in the industry. The measurement of the torque via strain gauges provides explicit results but can be difficult to implement on-site and is generally limited to a low rotation speed. The motor current measurement is easier to perform but does not always reflect the torque instantaneous variations. The measurement of the Instantaneous Angular Speed (IAS) presents an interesting alternative as several techniques exist which are relatively easy to install on-site. This is classically performed using optical encoders or magnetic pickup sensors. A lesser known technique is based on Laser Torsional Vibrometry (LTV), using parallel beam laser vibrometers, which has the advantage of being totally non-intrusive. One difficulty however of IAS based diagnosis techniques is then to interpret the IAS amplitude, due to the lack of rules and criteria in this domain, on contrary to translational vibration. Advantages of these different techniques for IAS on-site measurements are discussed, and applications are then presented on industrial cases: the test and certification of the coupling of a fuel injection pump and the torsional analysis of the flexible coupling of a Diesel-generator group.

1 Introduction

The measurement and analysis of torsional phenomena remains an uncommon and challenging task to perform in the industry. The measurement of the transmitted torque via strain gauges provides explicit results but can be difficult to implement on-site and is generally limited to a low rotation speed. The motor current measurement is an easier technique to perform but was shown to not always reflect the torque instantaneous variations, due to the filtering effect of the shaft line inertia on the higher frequency torque & speed variations. The measurement of the instantaneous angular speed (IAS) presents an interesting alternative as several techniques exist which are relatively easy to install on-site. This is classically performed using optical encoders or magnetic pickup sensors. The analysis of the IAS variations was shown to allow the detection of roller bearing faults [3-4]. Another technique is based on Laser Torsional Vibrometer (LTV), using parallel beam laser vibrometers, which has the advantage of being totally non-intrusive [5-6].

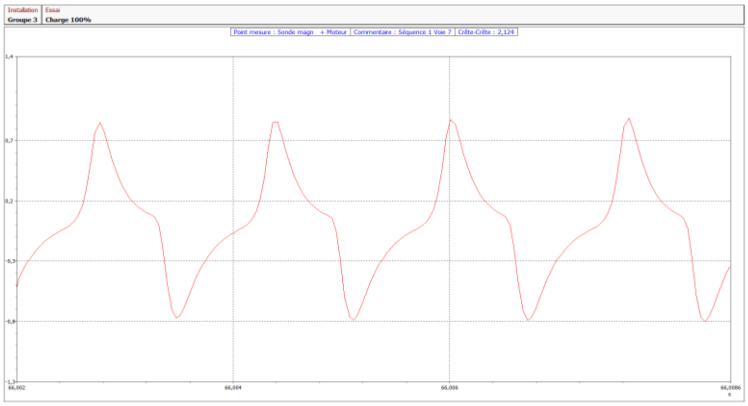
We first discuss the advantages of different techniques for IAS on-site measurements. We then present their application on industrial cases: first the test and certification of the coupling of a fuel injection pump, then the torsional analysis of a flexible coupling of Diesel-generator group.

2 Angular vibration measurement techniques

2.1 Use of impulse sensors (optical encoders & magnetic pickups)

The use of impulse sensors for IAS measurement from strip bands or optical encoders is quite common and well documented. The computation of the IAS can then be performed by the elapsed time method [8].

The IAS can also be measured by a magnetic pickup. In this case the computation is preferably done by frequency demodulation, as the measured signal is non-sinusoidal and modulated in amplitude (depending on the rotation speed).

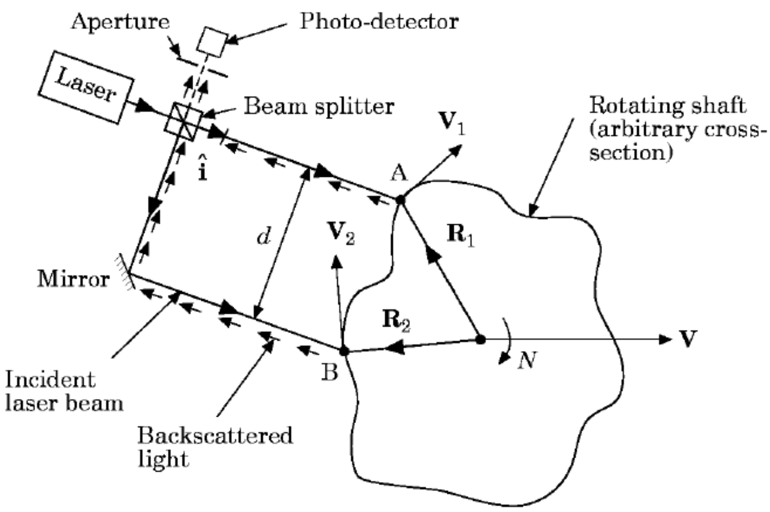


Signal measured by a magnetic pickup

2.2 The Laser Torsional Vibrometer

The Laser Torsional Vibrometer (LTV) is another technique that offers *in situ* measurement, thus avoiding machinery downtime and can function on rotating components of arbitrary shape. The optical geometry used makes the instrument insensitive to solid body oscillation of the target or operator as well as to the cross-sectional shape of the component [5].

The laser beam with wavelength λ is divided into two equal intensity parallel beams separated by distance *d*:



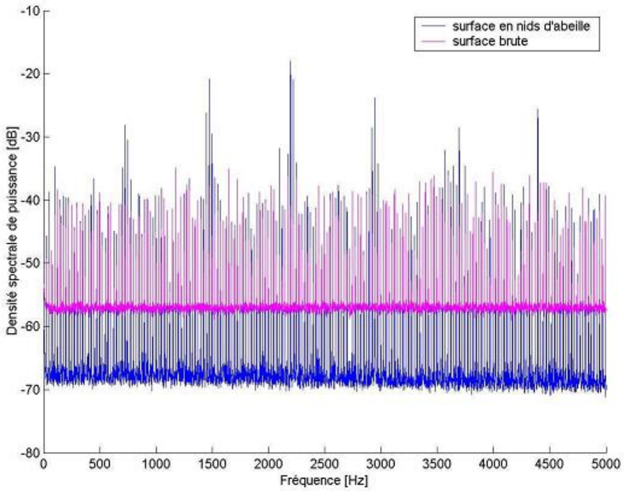
The laser torsional vibrometer optical geometry (picture taken from [5])

The ‘beat’ frequency between the two backscattered light beams received by the photo-detector corresponds to a Doppler frequency *fD*, which is directly proportional to the speed of rotation Ω of the target component:

$$fD=(2d/\lambda)\Omega$$

the fluctuating part of which is the IAS variation. The frequency response of the instrument is dictated by that of the demodulation system used and the usual bandwidth of practical interest is up to 10 kHz.

In practice however this technique is limited by the Signal / Noise ratio of the signal, which is influenced by a run-out phenomenon induced by the target surface roughness. This creates a speckle pattern periodicity at the shaft rotation. For use at very low levels of torsional vibration the speckle pattern periodicity can be attenuated by modulating the spatial position of the incident laser beams from side to side in a random manner.



Train of harmonic components induced by the run-out phenomenon

It should be noted that the setting and calibration of the LTV must be performed *in situ*, i.e. while the shaft is rotating, at least at a low speed.

Note that the LTV also offers the possibility of successive IAS measurement on different sections of the shaft line while the equipment is running. If a phase reference (tachymeter) is used, a torsional Operational Deformed Shape (ODS) of the shaft line can thus be performed.

2.3 In search of criteria and guiding rules for IAS assessment

One difficulty when dealing with angular vibrations is the lack of criterion in the literature in order to assess the maximum allowed amplitude of the measured IAS.

For combustion engines there is an industry regulation for the allowable magnitude of the Peak-Peak twist angle of the crankshaft, which must be below **0.4° PP** [7]. Some constructors have also defined their own criteria, depending on their experience. Note that Pr Nerubenko underlines in [7] that a *torsional vibration* is an angular vibration which implies a *twist* of the shaft, and must not be confounded with the *fluctuation of the rotation speed*, or the RPM non-regularity, which is another dynamical problem. The latter may be defined by the coefficient:

$$C = \Omega\_Peak\text{-}Peak / \Omega\_mean$$

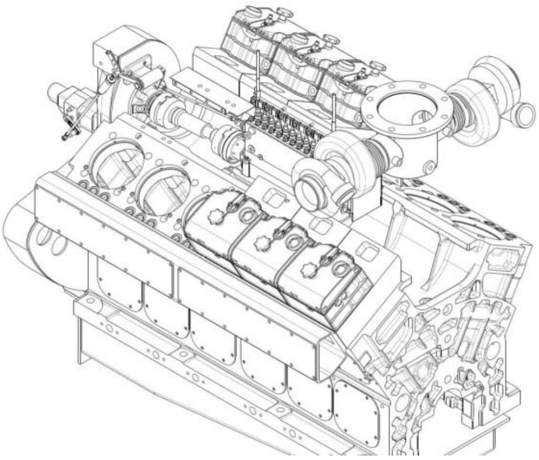
For combustion engines the guide numbers for coefficient *C* are in the range **0.6–1.2%**. Apart from the combustion engine industry we cannot seem to find any other criterion for the angular vibrations.

3 Industrial case studies

We present here applications of IAS measurement techniques to the torsional analysis of industrial equipments on two case studies.

3.1 Certification of a fuel injection pump coupling

This first application deals with a fuel injection pump of a 12V Diesel engine used on a ship. After installation of a new type of injection pump, the coupling of the pump happened to repeatedly break and was changed after only a few hours of service. It was then decided to test other types of coupling and to perform torsional vibration measurements, as a torsional resonance was suspected to be the cause of the damage.

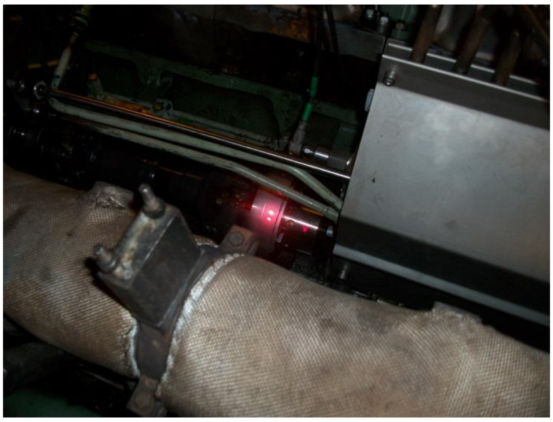


Injection pump installed in the V of the engine

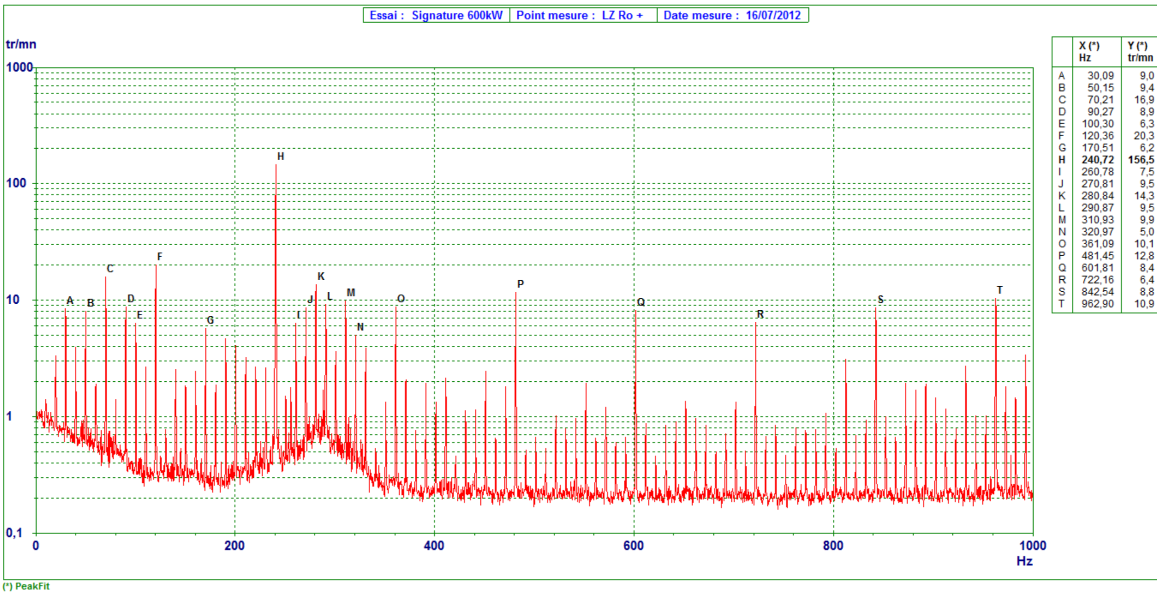
The pump is installed in the ‘V” of the engine and is run by a cardan coupling, which is run itself by the pinion cascade of the distribution. The methodology was as follow:

- Measurement with the initial coupling on the Diesel engine in order to qualify the existing system,
- Measurement with different couplings on a test bench and selection of that showing the best results,
- Measurement with the selected coupling on the ship for validation.

The measurements with the initial coupling were performed with the LTV device aiming the coupling of the injection pump, which is running at 600rpm:



The spectrum of the instantaneous angular speed (IAS) signal is showing an elevation of the background noise around 280Hz, which seems to amplify the spectral component at 2X the injection frequency (*Finj*=120Hz):

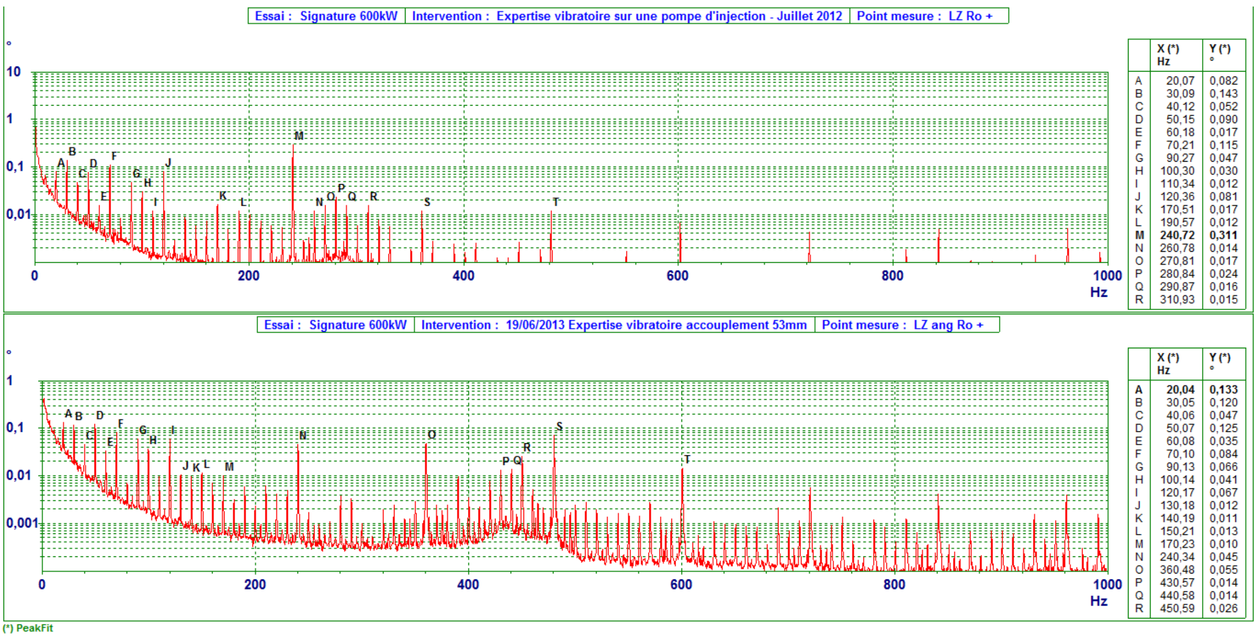


Spectrum of the IAS

The amplitude of the IAS variation at 2X Finj is 156.5rpm Peak-Peak, corresponding to an angular variation of 0.31° 0-P. A limit value was defined empirically for any component of the integrated IAS spectrum, at **0.25° 0-P**.

The injection pump was then tested on a test bench with different types of couplings (1 cardan & 3 disk couplings with different diameters). The best results were obtained with a 53mm diameter disk-coupling.

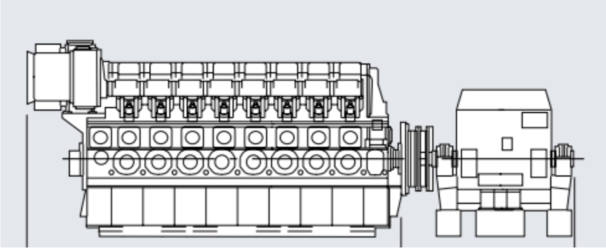
This coupling was then mounted on the engine on board for an endurance test. The amplitudes of the IAS spectral components are significantly lower compared to the original coupling and below the criterion of 0.25° 0-P. They also remain stable after 4 months of service.



Comparison of the angular vibration spectra (in ° 0-P) with the original (top) and new coupling (bottom)

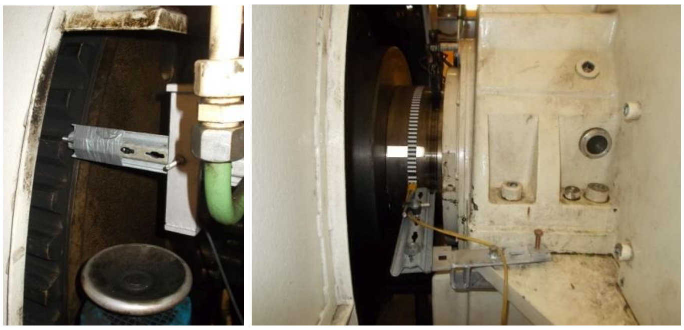
3.2 Torsional analysis of a flexible coupling

This second case study deals with the torsional analysis of a coupling of a high power Diesel group. The equipment is constituted by an 18V Diesel engine driving a generator via a flexible coupling. The shaft line of the group is running at 500rpm.



Diesel engine and generator group

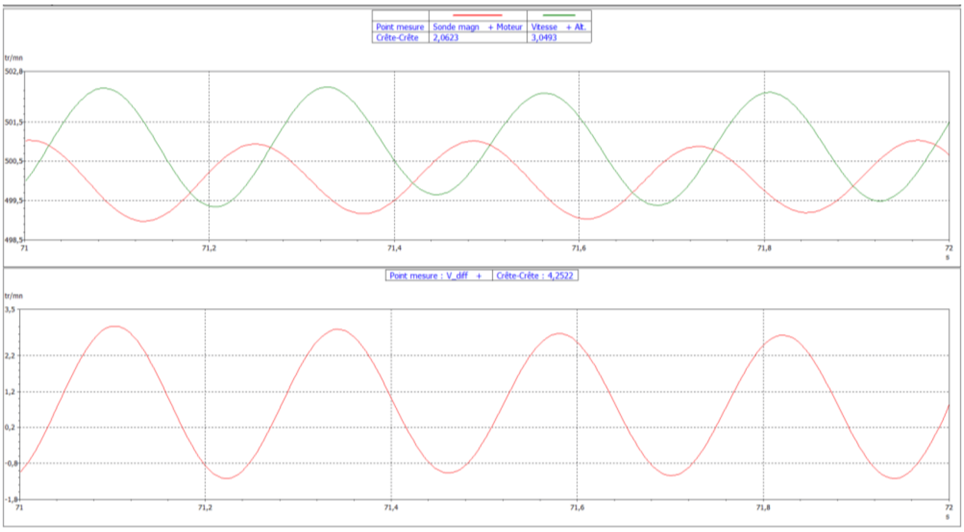
After a sudden and destructive damage of the coupling, it was decided to perform IAS measurement on each side of the coupling in order to analyse its torsional behaviour in service. On the generator side the IAS was measured by using an optical sensor and a strip band with 125 pulses. On the engine side we used a magnetic pickup placed near the toothed wheel of the engine (74 teeth).



Speed measurements on the engine and on the generator

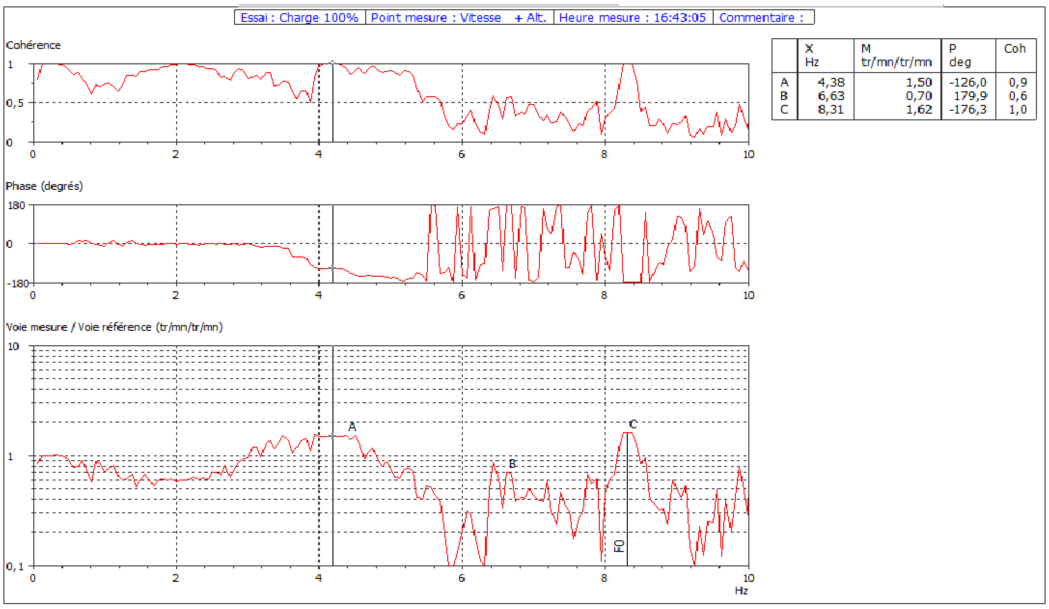
Note that the imperfect junction of the strip band stuck on the generator shaft is inducing periodic spikes at the rotation frequency. These spikes can then be suppressed by a dedicated algorithm. Besides, an advantage of these spikes is to provide a 1X/rev phase reference on the generator shaft.

The analysis of the IAS when the group is running at full load reveals an IAS fluctuation at the combustion cycle frequency of the Diesel engine (i.e. half the rotation frequency) which is present on each side of the coupling. Moreover we observe that this component is phased out and amplified from the motor side to the generator side. The associated speed fluctuation due to this component is about 2rpm PP on the motor side and 3rpm PP on the generator side. This corresponds to a coefficient C of speed non-regularity of 0.4% and 0.6% respectively, which seems acceptable. However the fluctuation of the differential speed between the engine & generator is higher (4.25rpm PP), and the corresponding twist of the coupling is about 1° PP.



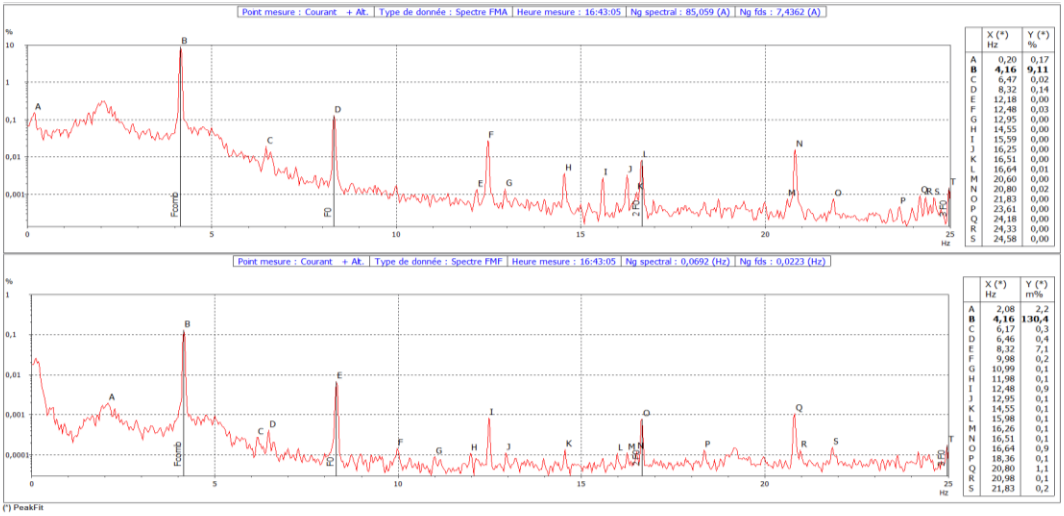
Filtered IAS on the motor & generator sides and differential speed showing a fluctuation at the combustion cycle frequency

The amplification and the phasing of the IAS component at the cycle frequency seem to indicate the proximity of a torsional modal frequency of the shaft line that may amplify the cycle frequency component at 4.17Hz. This seems to be confirmed by the following Frequency Response Function (FRF) calculated between the IAS of the engine and of the generator, which shows a 90° phase lag at a frequency slightly under 4Hz.



FRF calculated between the engine & generator IAS

A measurement of the electrical current was also performed on the generator and shows a strong amplitude modulation at the cycle frequency (9%). Thus the observed IAS fluctuation at the cycle frequency is inducing a torque modulation and so a modulation of the generated electrical power. This modulation is then inducing a torsional fatigue of the elements of the shaft line, especially of the coupling.



Analysis of the generator current amplitude & frequency modulation functions at full load

We also note the presence of an amplification of the background noise around 2Hz on the current amplitude modulation spectrum, which may indicate a torsional modal frequency of the shaft line. This modal frequency is also observed by a transient oscillation on the IAS signals at the moment of the electrical coupling of the generator. Thus it seems to involve the electromagnetic forces of the generator.

We attempted to perform a torsional modelling of the shaft line as in [9], however some parameters still remain unknown: the inertia of the engine and also the torsional stiffness due to the electromagnetic forces of the generator (which seems difficult to estimate from its electrical properties). Further tests are yet to be performed on this group, e.g. testing a flexible coupling with a lower torsional stiffness in order to reduce the incriminated torsional modal frequency close to the combustion cycle frequency.

4 Conclusion

We attempted here to show the interest of different IAS measurement techniques for the torsional analysis on industrial case studies. The use of a specific technique will depend on the application and on the possibilities on site. Advantage of the VRL is to be totally non-intrusive and to avoid machine downtime; however its setting must be performed while the equipment is running.

We also showed the advantage of combining IAS measurement with other measurements, such as the electrical current or the transmitted torque, in order to obtain a full understanding of the torsional behaviour of the equipment.

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