DYNAMIC PRESSURE SENSORS: FREQUENCY RESPONSE INVESTIGATION AND CALIBRATION METHODOLOGIES

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ABSTRACT

Design and experimental research on turbo-machines need more and more deepened flow characteristics acquaintance. For this reason the development of experimental analysis systems allowing the study of high frequency phenomena involving in the flow is necessary. On the market many types of sensors for dynamic pressure evaluation with very high natural frequency are available. Checking if the sensor is working properly and verifying their calibration is extremely difficult because of realizing a known frequency pressure wave. These sensors are usually calibrated using a pressure step generated, for example, in a shock tube or using falling weight and analysing the probe frequency answer. The correct frequency calibration depends very much on pressure pulse rise time.

In this paper an alternative, simpler, method is presented. A Speaker is used to generate a pressure wave of known frequency (the speaker allows to reach also high frequencies). In this way it is possible to characterize the frequency response and the frequency resolution of the sensor. Using an indirect process it is possibly to value the sensibility too. This system also allows to test the sensor with a base pressure to understand how this modifies its answer. The problems encountered to realize this system and to generate such wave are also reported.

1. INTRODUCTION

In the last years the technological development in the field of the piezoelectric and piezo-resistive sensors allowed to use the good frequency response characteristics of these materials for improvement of Fast Response Pressure Sensors. With these it is possible to execute researches aimed at the study of the phenomena that evolve at very high frequency, as turbulence. The instruments usable for this high frequency study were limited to the "hot-wire anemometers", prone to breakage in high-pressure, high-speed flows, or some laser techniques (i.e. LDV) that however require long run-time. Both of them, moreover, measure the flow speed and therefore do not give any direct information on loss production.

A standard use of fast response pressure sensors is the study of turbo-machinery flow instability as stall, rotating stall and surge. These same sensors, without the cover, are used for the realization of Fast Response Aerodynamic Probe (FRAP®) or to study the flow near the surface of turbo-machinery components. In those cases, thanks to the sensing elements small dimensions, it has been possible, for example, to realize a three millimetres diameter three-hole probe including a system for destruction of vortex shedding (J. F. Brouckaert et al. 1998) or equip the blades surface of a turbine stage with some piezo-resistive pressure sensors in order to study the flow near the wall (To J. Dietz and R.W. Ainsworth 1992).

Parallel researches were developed in order to get detailed characteristics of sensors (piezoelectric or piezo-resistive). Deepened researches were made on time stability (in the case of continuous pressure sensitive probes) and on temperature variations sensibility (self-heating too), highlighting which are the problems of these probes and showing the tests for the calibration of these factors (Kupferschmied et al. 1998 and R.W. Ainsworth et al 1990). As far as the frequency response calibration the method commonly used is subjecting the probe to a pressure step and analysing the response in frequencies domain. The system generally used is a "gas-driven shock tube": an about 2,15 meters long per 50 mm internal diameter tube divided in two principal chamber by a replaceable aluminium diaphragm. The first chamber is pressurized with the driver gas (Air, Nitrogen or Helium) until the pre-selected diaphragm bursts generating a well-formed shock wave that, after an expansion chamber, reach the test sensor. This system allows to characterize the resonance frequencies of the sensing element (also over 500kHz) and of the cavity in which it is inserted (approximately 90-100 kHz). With this method the pressure step has a rise time of 1 ns.

Other commercial systems use different principles in order to generate step of pressure (fast valves, falling of weight on a pressure chamber), but with longer rise time (of milliseconds order) and therefore less efficient for the frequency response determination. These last systems in fact don't have as primary aim the probe spectrum, but the sensibility ($\Delta V/\Delta P$) determination as in the piezoelectric probes case where a static analysis is not possible. Generally in the method previously described it is possible to use, together with the calibrating probe, also another one with stable characteristics as reference.

The frequency response to a pressure step of a dynamics probe is strongly influenced by pulse rise time and by the distance covered during its propagation (in terms of distance and reflections). The only valid system looks to be the "shock tube" since it has very small rise time. However it needs of cumbersome and sophisticated structures. For this reason generally these probes are frequency calibrated only at the sale moment by the manufacturer and no more verified.

The proposed system is an alternative calibration method with the characteristics of being easily realisable and usable so as to execute the probe calibration in terms of resonant frequency investigation, sensibility and frequency resolution every time is needed.

2. MEASUREMENT SYSTEM

The base idea is to use, as pressure waves generator, a speaker fed by an adequately amplified signal of known frequency. By varying the signal frequency sent to the speaker, it is possible to analyse the probe response for all the spectrum of interest with remarkable accuracy and resolution. Eventually a reference probe, symmetrically placed regarding the sound source, can be used like control of the speaker behaviour or like comparison for the calibrating probe. The system has the advantage to be quite portable and to allow verification of the probe conditions in simple way. Putting the system in a pressure chamber is it possible to make test with a known base pressure. In this case, another characteristic frequency of the system is introduced and problems of sonorous reflection can occur. These have to be adequately dampened. In any case the frequency response study in presence of a base pressure allows to verify the probe behaviour in the real working condition simulating turbo-machinery environments or eventual not linearity of its behaviour.

2.1. Instrumentation set up

The system (Figure 2-1) is composed of two main parts: one that generates the pressure signal and the other that acquires and processes the sensors output. A standard signal generator HP 33120A was used to generate a sinusoidal signal of variable frequency. This signal was sent to the speaker driving circuit that amplify and send it to the speaker. Here the sensors, adequately pointed to the sound source using a template, catch it. Their signals arrive to a power signal conditioner and then acquired by the digital analyser TEKTRONIX TDS 744 triggered with the signal of wave generator and controlled by Pc using GPIB interface and a LabView written software. The same software is used for analysing the digital signal.

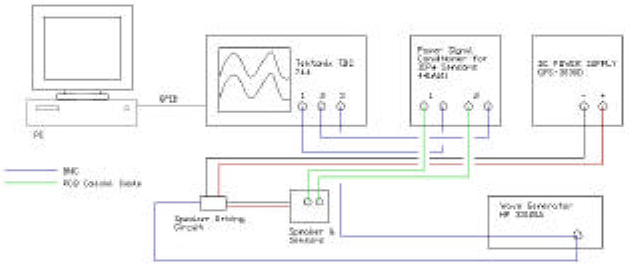

Figure 2-1. Instrumentation set up.

2.2. Sensors

Two never used ICP® (Integrated Circuit Piezoelectric) sensors by PCB PIEZOTRONICS Inc. model J112 A21, serial number 18534 and 18533, are tested (see Figure 2-2, left). These sensors have a piezoelectric sensing element (unable to determine accurately the DC value) and an internal microelectronic signal conditioner that allow to have a low impedance output signal with high signal-to noise ratio. This able the sensor to be used in industrial application (stall and surge studies) without disturbs danger. Producing house gives for these sensors two linear calibration, one at full scale and one 10% of scale. They have a sensitivity of 7.3 ± 1.5 mV/kPa (i.e.50 ± 10 mV/PSI), a resolution of 0.014 kPa and a resonant frequency ≥ 250 kHz. They two mount an adaptor model 062 A21 to prevent ground loop and allow a simpler mounting. As power signal conditioner is used the PCB 441A101 for ICP® sensors with a fixed gain of 100 times.

For further studies a KULITE XCS-190-5D sensor was used too (see Figure 2-2, right). This is a 5 PSI maximum pressure piezo-resistive probe with a typical natural frequency about 150 kHz and sensitivity about 50mV/PSID. It is DC sensitive and so it could be statically calibrate. KULITE sensor was used with the INSTRUMENT DIVISION Signal Conditioning Amplifier model 2311. The output was feed to one of the four TDS channels.

Figure 2-2. PCBs 18533, 18534 (left) and KULITE (right) sensors photos.

For PCBs sensors the producing house calibration certificate gives the following values (Table 2-1):

	18533	18533	18534	18534
Range (PSI)	**0-100**	**0-10 I**	**0-100**	**0-10**
Sensit. (mV/PSI)	50.33	50.84	51.51	51.71
Linearity (%FS)	0.13	0.2	0.11	0.24
Nat. Freq. (kHz)	300	300	350	350
Time Const. (s)	2	2	1.8	1.8

Table 2-1. Producing house PCBs calibration values.

The Time Constant value determines the smallest frequencies that can be acquired by the sensor and not confused for a DC signal. How can be seen from Table 2-1 very high natural frequencies are grant for these sensors.

2.3. Speaker

CYBERNECK PIEZOCERAMICS supplied the speaker (Figure 2-3). It is built in piezo-ceramics so no magnetic fields are product. The house assures acoustic properties variation within ± 3.5 db due to environmental condition. The sound pressure emitted for a frequency of 1 kHz with an input voltage of 7 Vrms is 92 db at 32 cm and 85db at 1m.

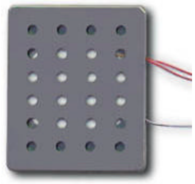

Figure 2-3. Speaker's photo.

A circuit that amplify the signal of wave generator (always sinusoidal of 1 V_{pk} for each frequency) drives the speaker. The speaker impedance decay following an exponential law when the frequency increase. Producing house speaker characteristic are reported in Figure 2-4.

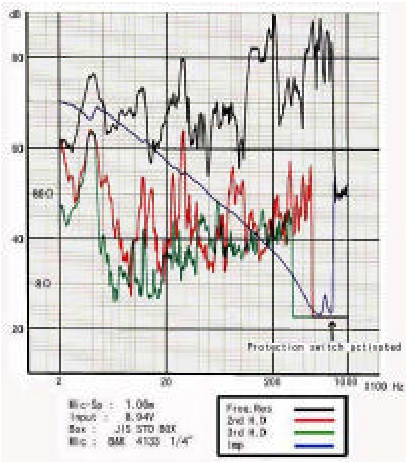

Figure 2-4. Producing house speaker characteristics

In our system the protecting switch is not present so higher frequencies could be reached.

3. PRELIMINARY CONFIGURATION

Particular attention goes to the system with which the probes are pointed at the sonorous source (template and sensor support). The first studies in such sense have revealed a great response dependency with the relative position regarding the source and with the probe support realisation: various support structures have been tested. The same speaker support has great influence. Interferences in the signal emission due to interactions with the speaker support plan have been noticed: the speaker back and front face emit signals that are 180° phased. Tests with suspended speaker have been executed to eliminate this kind of disturb. Since the sound pressure level emitted by the speaker for each frequency is unknown, two sensors for a relative comparison are always used.

The first configuration (Figure 3-1) was simply formed by the speaker and a plastic template for supporting the sensors and dumping vibrations coming from the metallic speaker structure. In this configuration it has two holes so each sensor sees only one speaker hole. The two holes, because of the system geometry, could not be symmetric respect to the speaker centre. The sensors beat on the template surface to have a position reference.

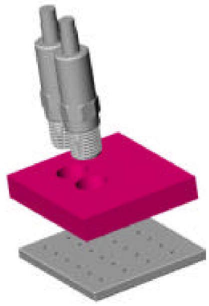

Figure 3-1. First tested configuration.

The signal acquired by PCBs results very distorted and strictly linked to how the speaker lie on the support plane since it reflects the back face signal. A suspended configuration was tested to avoid this interference. This gave the best results: the sensors outputs were extremely pure: sine waves without any harmonics. Although that, the probe output sill depended a lot on the relative position on the template (speaker source hole at which they were pointed).

For getting a diffuse source, square formed aluminium beams of different thickness were interposed between the template (used only as support) and the speaker. Still big difference between the signals acquired in the two different positions exists independently by the sensor used (Figure 3-2).

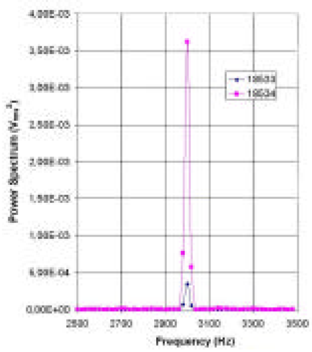

Figure 3-2. PCB in one position and inverted.

The most the PCB is near the centre the most the signal is high, although the box presence should have made the sound pressure level more homogeneous.

4. FINAL CONFIGURATION

The previous considerations have led to a new configuration that grants the same sound pressure level on the two sensors. Two PCBs are symmetrically screwed down in a Y joint respect a hole on a metallic template. On the template back face the speaker lodge is milled so that one hole of it is lined to the one on the template. Between the template and the speaker a holed paper foil is set to prevent vibration propagation. An open aluminium squared box is used to and to avoid inferences with the back face signal and allow an easy packaging. The system was suspended during the tests. In this way no interference between front and back signal are present and pure sine wave are obtained for almost all frequency. This configuration revels great signal repeatability and stability to external factor and so many tests have been done. Another similar joint is also prepared. One of the two branches was modify to receive the previously described KULITE sensor.

The acquisition procedure was the following one. The Power Spectrum analysis was applied to a mean of generally five same phase time domain acquisitions for each frequency value set on the wave generator. If the Power spectrum peak has a frequency different from which of the wave generator means the signal could be confused with noise and that point is considered a sensor blind frequency. The noise level, with a mean on five waves, is about 1.5 x 10^{-4} V_{pk} (the signal is 100 time amplified). Generally the number of time domain wave with which the mean is done is about five, only when the frequency become greater the number is increased. This led the noise level to decrease to 0.5 x 10^{-4} V_{pk} for KULITE sensor, whereas no change is appreciable for PCB sensors. The Signal to Noise ratio (SNR) was kept to two. In the graphs that follow the KULITE sensor tension value is always reported with the same amplification of the PCB ones. Below are reported the test executed with this configuration on PCBs and KULITE sensors.

4.1. Comparison PCBs 18533 –18534

The first important check was to compare the two PCBs signals when their position was inverted: This test has been done for a frequency range between 100 and 2500 Hz (Figure 4-1).

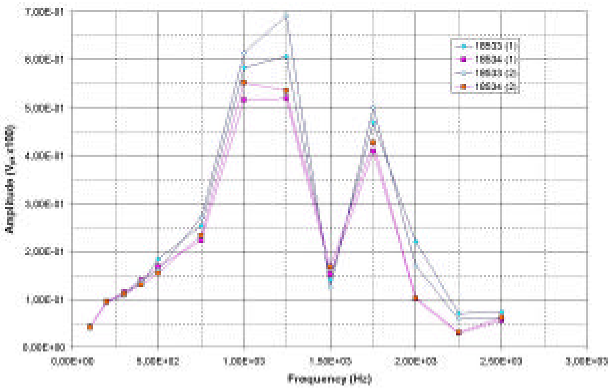

Figure 4-1. Comparison between PCBs answer obtained inverting their position in the Y joint.

How can be clearly seen there is a very good agreement between the two situations. This test assures to have a quite similar pressure on the two probes. The next step was to scan the probes answer changing the frequency value.

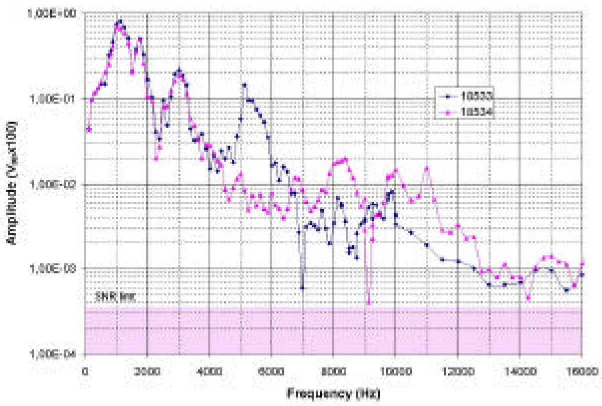

Figure 4-2. PCBs answers for frequency up to 16 kHz.

Two sensors have the same trend for frequencies under 4000Hz, after that value many differences could be noticed. For example PCB 18533 have an evident problem around 7000 Hz instead of 18534 where the flaw is near 9000 Hz). How can be seen these graphs have the same trend of that of previous configuration, but with quite different value. The study continued in greater frequencies range, acquiring more spaced point, to see which were the limits reachable by the sensors. The results are reported in Figure 4-3.

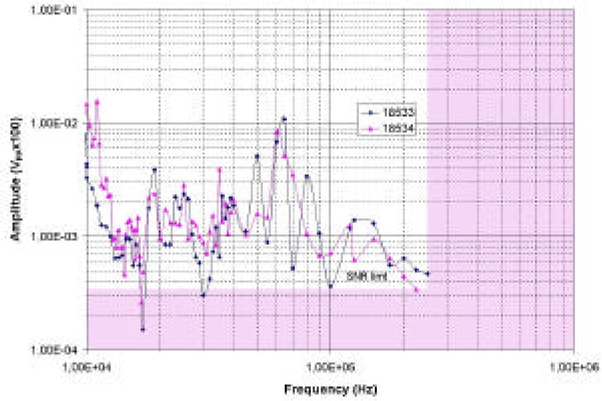

Figure 4-3. PCBs answers for frequencies over 10 kHz.

In this graph can be seen a very variable trend even if the absolute value become smaller and smaller. Around a frequency of 250 kHz the PCBs do not see the peak value at the same frequency of the signal emitted by the speaker. Many tests were done on the same probes in the same frequency range and the resulting curves showed the same trend and values.

4.2. Comparison of PCBs 18533 and 18534 with KULITE sensor

This kind of test is which that gave more information on the investigated probe. KULITE sensor could be calibrated with a static pressure generator. The one produced by SCANDURA was used to obtain the calibration curve of the sensor used. With the calibration function it is possible to value the pressure acting over the sensor measuring the output tension. It is not possible to surely affirm that the pressure is the same on both the two sensors like in the previous configuration (here, was not possible to invert the sensor for geometrical differences). The system was done so as to put the two sensors sensing surface at the same distance from the sound source. Changing the sensors position (adding a washer for example) negligible variations in the signal could be noticed. This can be seen as a good agreement between the two-pressure levels.
KULITE was calibrated before starting the test. The calibration function is reported Figure 4-4. It was obviously done for low pressure.

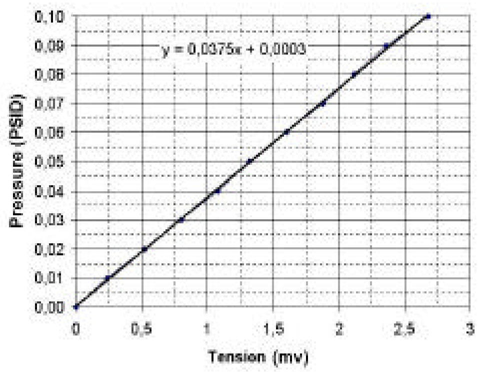

Figure 4-4. KULITE sensor calibration.

With this configuration two series of test were made, one for each PCB sensor. How can be seen in Figure 4-5 the KULITE sensor gives for each test almost the same answer. For upper frequency, where less measurement point was taken, the signals become more different (Figure 4-6). The analysis for frequency over 16 kHz is done to find sensor working limit and resonance frequencies, not to compare their answers.

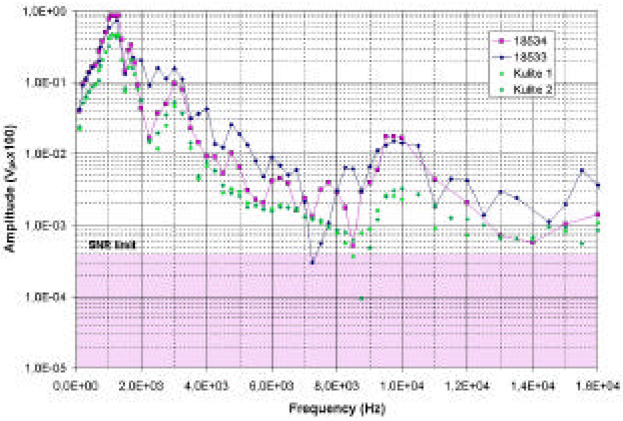

Figure 4-5. PCBs and KULITE answers (up to 16 kHz).

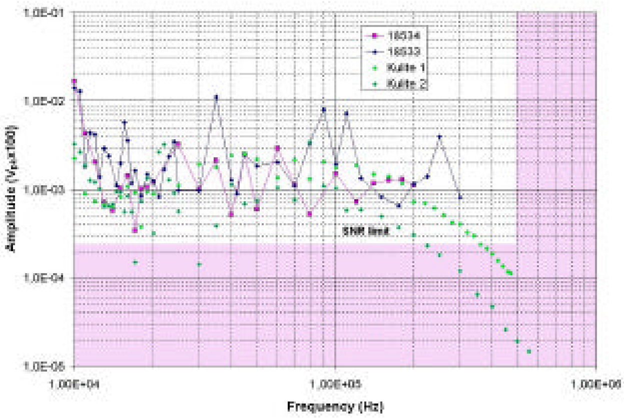

Figure 4-6. PCBs and KULITE answers (over 10 kHz).

Each sensor has a trend that is quite similar to that of previously used configuration (two PCB without KULITE).
It has to be noticed that often even if the signal is below the SNR limit, the peak is equally over the noise and clearly visible. For KULITE sensor the peak is still visible up to frequencies about 500 kHz, while PCB sensors arrive at about 250 kHz. For many frequencies the KULITE sensor answer present very small harmonics up to the 5 per one. Some images taken by TDS digital scanner for different speaker frequencies are reported below (Figure 4-7 and Figure 4-8).

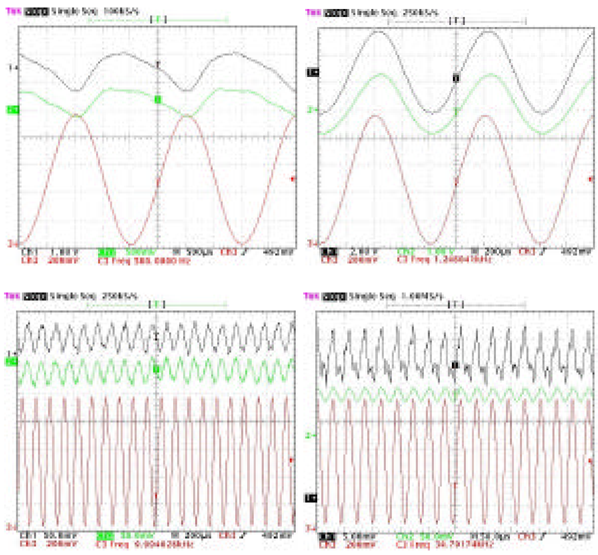

Figure 4-7. TDS images of PCB 18533 (Green), KULITE (Black) and wave generator (Red) signal for different frequencies (0.5, 1.25, 10, 35 kHz).

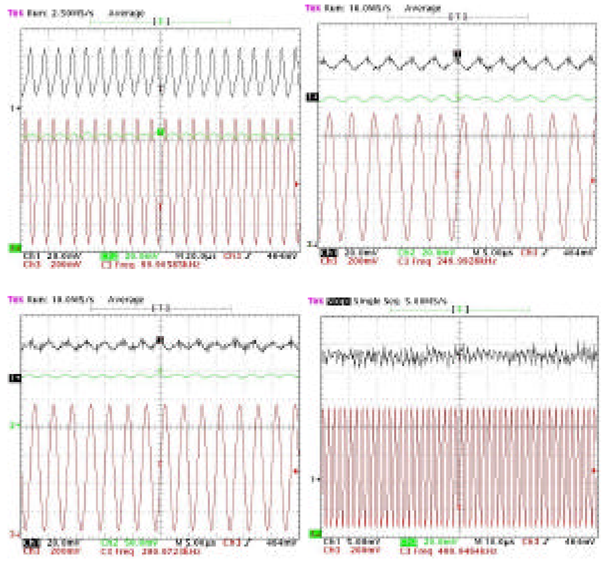

Figure 4-8. TDS images of PCB 18534 (Green), KULITE (Black) and wave generator (Red) signal for different frequencies (100, 250, 300, 500 kHz).

From these could be seen how the signal is good also for high frequencies. Moreover the system shows a high response in terms of resolution: frequencies variations of 0.2 Hz was given to the speaker in a wide range of frequencies. These variations were clearly viewed by the three sensors. Smallest steps are not been tested.

4.3. PCBs sensitivity calibration

For frequencies up to about 16 kHz KULITE sensor gives a very smooth answer, with few peaks. The same thing cannot be said for PCBs sensor. The variable trend of KULITE sensor can be caused by the different speaker answer for each frequency. The PCBs course suggests a different sensitivity value for each frequency or a micro-resonance presence.
Comparing the sensors answers, assuming the same pressure acting against them and using the KULITE calibration function, very interesting value can be extracted (Figure 4-9).

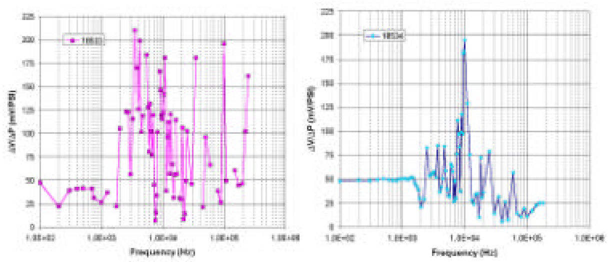

Figure 4-9. PCB 18533 and 18534 DV/DP (mV/PSI).

Sensor 18534 (graph on the right) for frequencies below 1600 Hz has a ΔV/ΔP constant value around 49.5 ± 1.4 mV/PSI. For upper frequency this value becomes much more variable. Sensor 18533 (graph on the left) has a ΔV/ΔP constant range smaller than the other probe and with more dispersion. For this sensor the zone where ΔV/ΔP value is almost constant is between 300 and 700 Hz (40.6 ± 1.2 mV/PSI). For a frequencies range between 0 and 1600 Hz ΔV/ΔP is 36.1 ± 8.1 mV/PSI. Why only the first part of the frequencies range as a constant ΔV/ΔP is a problem still not clear or, better, is not clear if this phenomenon are bound to the sensors or to the speaker. It was thought that the speaker diver circuit did not send a signal of constant amplitude to the speaker for each frequencies how is imaginable since the speaker impedance decrease with frequencies. So the AC tension incoming in the speaker was measured to see if a big amplitude variation fell in that zone (Figure 4-10).

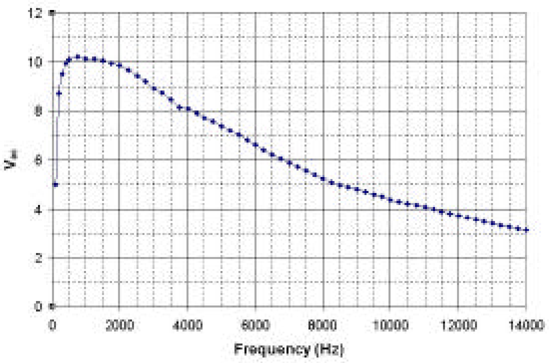

Figure 4-10. Speaker incoming AC tension.

How can be seen the AC tension keep itself almost constant until 2000 kHz where the ΔV/ΔP of the two sensor is already become variable. It has to be noticed that all the phenomena involving in a turbo-machine for which these sensor are standard used, are for frequency smallest than 2000 Hz.

4.4. Resonance frequencies individuation

Due to the characteristics of the system realized it is possible to study the resonance frequencies of Dynamic Pressure Sensors. Two example are reported below, Figure 4-11, in which is clearly visible a resonance frequency for KULITE sensor (≈ 80 kHz) and one for PCB sensor (≈ 91 kHz).

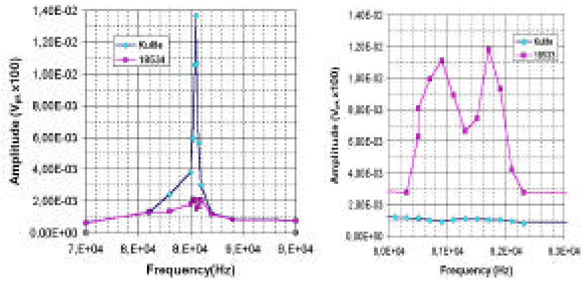

Figure 4-11. KULITE and PCB resonance.

These are obviously sensors resonances because only one sensor at time feels the great amplitude variation. If both of them would have felt an amplitude variation, probably, it would be a speaker resonance since the two sensors are different. The doubt still persists if both sensors are of the same type. It is quite important to know if any resonance frequency is present in measurement range in which the sensor will be employed to be sure to do not have wrong information.

5. CONCLUSIONS

Form the preliminary studies emerge that it is possible to realize a practical system for Fast Response Dynamic Pressure Probe checking using a speaker as oscillating pressure source. This allows controlling the probe functionality every time is needed (for example before its use). Some attentions have to be paid:

- The speaker has to have an appropriate sonorous power (in order to contrast the signal dissipation in air) and emission characteristic (maximum frequency reachable).
- Realisation of an appropriate amplification circuit of the signal sent to the speaker that does not introduce deformations for the studied frequencies.
- Realisation of a template that makes the speaker as similar as possible to a punctual source.
- Realisation of a steady support with opportune references for placing the probes always at the same distance from the source.
- Realisation of a support-source and support-base connection system that allows to eliminate disturbs due to the interaction between the two elements (the best solution is a suspended equipment)

Basing on these principles a system was realized. The tests done with this on two PCBs allow to verify their frequency resolution and acquisition limits. It is, moreover, possible to verify if the application range in which they will be used is resonance frequencies free. Using a previously calibrate DC sensitive sensor (KULITE) it is possible, with some supposition, get a ΔV/ΔP value in the using common range, also for piezo-electric sensor. In this way it is possible, for example, to know the pressure fluctuation value due to the passage of a stall cell.

The system can be made automatic with a little modification of the software, simply inserting a sub-routine that commands the wave generator and change the frequency after each acquisition. In this way it is possible to scan all the functional range with a good number of point.

Another test and modification that could be done is to change the sensor support as so to be able to invert the PCB and the KULITE sensor to verify the pressure in both the position. Another attempt that could be done is to substitute the speaker with a different one for seeing how the sensors answers change. Future analysis can study the sensor answer when a base pressure is present. This involves the realization of a hermetic cavity in which lodging the sensors.

6. ACKNOWLEDGMENTS

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7. NOMENCLATURE

V_{pk} : peak to peak tension value (V)
V_{rms}^2 : effective tension (V^2)

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