Analysis and Visualization
of Big Data Systems and
High Performance Computing

Assignment

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December 2019

MSc Aerospace Computational Engineering

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Abstract

The aim of this document is to perform digital signal processing of Computational Fluid Dynamics data obtained from a research document conducted by (Forestier, Jacquin and Geffroy, 2003).

In the whole process, further knowledge in Aeroacoustics must be acquired to understand the phenomena that take place in the cavities and that cause results to behave as they do. Once achieved, several hurdles inherent in signals (such as leakage, aliasing, noise, etc…) will be faced by using spectral analysis and filtering techniques - with the MATLAB software - in order to withdraw the desired information.

Introduction

If a single equation of the relevant Aerospace environment had to be highlighted, it would probably be the Navier-Stokes equations. Their importance remains in their ability to describe and predict the behavior of any fluid in consonance with the variation of their extensive variables.

However, the hardness and hostility (introduced mainly by non-linearity and turbulence modelling) to solve them analytically proves the need of obtaining their integrated results through other means.

Due to this, other approaches involving numerical methods as CFD have been widely developed and many experiments have been performed to be enable a better understanding on fluids' unpredictable nature.

Depending on the approach, the results expected, the scope of the problem faced and the assumable computational cost, the methods involved will rely on different types of simulations.

From the most basic and quick, RANS, to the most complete but excessively high in terms of computational costs, DNS, we can find a fan of possibilities in which Large Eddy Simulations (LES), and Hybrid Methods suppose an intermediate step with its own benefits and cons and therefore own applicability. However, nowadays, every expert seems to rely in a particular type of simulation and there is no united theory or agreement in which approach is more accurate and beneficial in terms of physical meaning. Hence, most of times, the choice of the simulation entails a compromise solution between computational cost and results.

However, the study of fluids can also be conducted depending on the particularized study of their variables. A clear example of it would be the main thermodynamic basis in the study of the combustors. Nonetheless, one of the main magnitudes of fluid dynamics is the term of pressure, which can describe much of the phenomena that takes place (shock waves, shear layer mixing, Prandtl-Meyer expansions, indirect turbulence, etc...). Since sound is a pressure wave and can be related to other fluid magnitudes (such as Mach number), its study may lead to further knowledge on fluids.

This idea led to the creation of a new sub-science called Aeroacoustics inherent in Fluid Dynamics and can show some relationship between the noise caused and the dynamic state of the fluid. Sometimes, it can be more profitable to analyze than traditional CFD methods as noise can be easily obtained by tiny microphones and signals can be processed with complex modern signal algorithms – which can reveal a huge amount of information that may remain invisible through other observational procedures. The main responsible for this development is Jean-Baptiste Joseph Fourier, whose astonishing contributions will be seized in the following pages.

Since the first strong foundations of Aeroacoustics introduced by Lighthill around 1920, further investigation by both CFD and experiments have been performed. One of them is the paper we are currently analyzing from which our study has been withdrawn: it is examined the conduct of a turbulent fluid over a cavity under the evaluated experimental conditions. Then, it is compared to CFD simulation data in order to verify the accuracy of the simulation but its ability to predict physical phenomena as well.

Problem characteristics

The problem faced is more about signal processing than fluid dynamics, however, we will inform about the origin of the given data. It is obtained by experimental and simulation of a cavity, carried out by:(Forestier, Jacquin and Geffroy, 2003) .

The main conditions to be considered (which has been proved to be accurately evaluated in 2-D) have been:

· Cavity geometry: L/D=0.42, L= 50 mm, D= 120 mm, W= 120 mm.

· Flow: M=0.8, Re_{Θ}=11.145, $Re_L \approx$ 860.000.

Additionally, serve the following illustration (Figure 1) as the two-dimensional scheme of the problem:

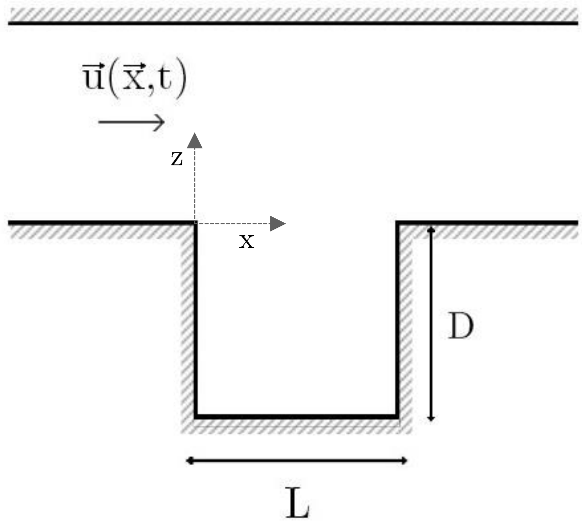

Figure 1. Flow over a cavity scheme

According to elementary fluid mechanics (see the classic problem of the back-step flow), in a big picture, the formation of two recirculation zones with general dynamics such as picture 2 could be expected:

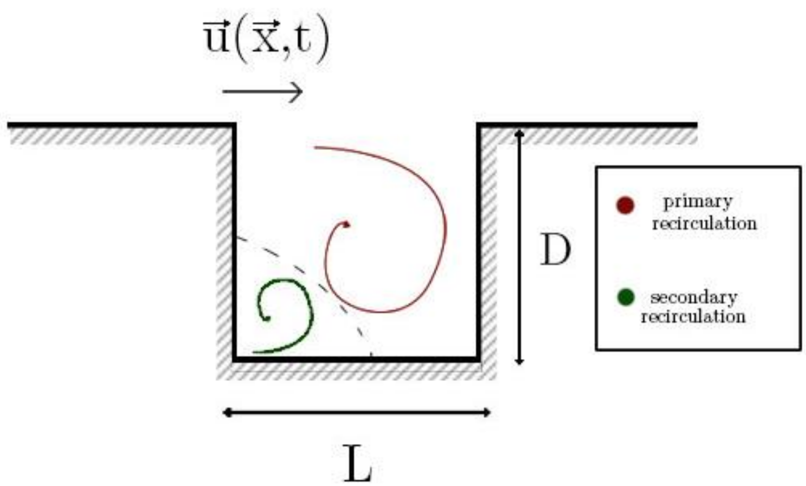

Figure 2. Main recirculation zones expected

However, many other phenomena that take place such as shear layer mixture, noise generation, shock waves, vorticity, turbulence, etc… are not as easily obtained. Hence, it is stated the need of conducting experiments and simulations to know more about the fluid dynamics in these structures. This problem acquires more relevance when military or high flow planes are studied, since these structures are common and lead to loud sound production but mean flow perturbation as well. That is why, a large literature and research about this scenario can be found.

In our case, the pressure variation along time in a particular point of the deep cavity (x=0 mm, y= 0 mm, z=-35 mm according to Figure 1's reference axis) acquired by simulation has been given, but also the experimental data expressing the Sound Pressure Level (SPL) in dB against frequency. Hence, our main objective is to process both signals in order to fight undesirable effects introduced such as noise, aliasing and leakage and to understand the fluid phenomena that takes place by analyzing the results.

Methodology

As it has been already stated, we will try to mainly fight aliasing and leakage in the CFD data. This whole process will be performed by the software MATLAB.

To begin with, the first step to carry out is to import both files ("pressure_raw_cfd.dat" and "pressure_experiment.dat") into the MATLAB environment. As it can be seen (see Figure 3), if both files are plotted, they don't look alike at all since the CFD data states pressure against time and the experimental SPL against frequency. Additionally, the length of each vectors is not the same (N_{CFD}=150.000 and N_{EXP}= 206) so likely the sampling frequency will not be the same at all either. Due to this, we may expect some issues which will be explained later on.

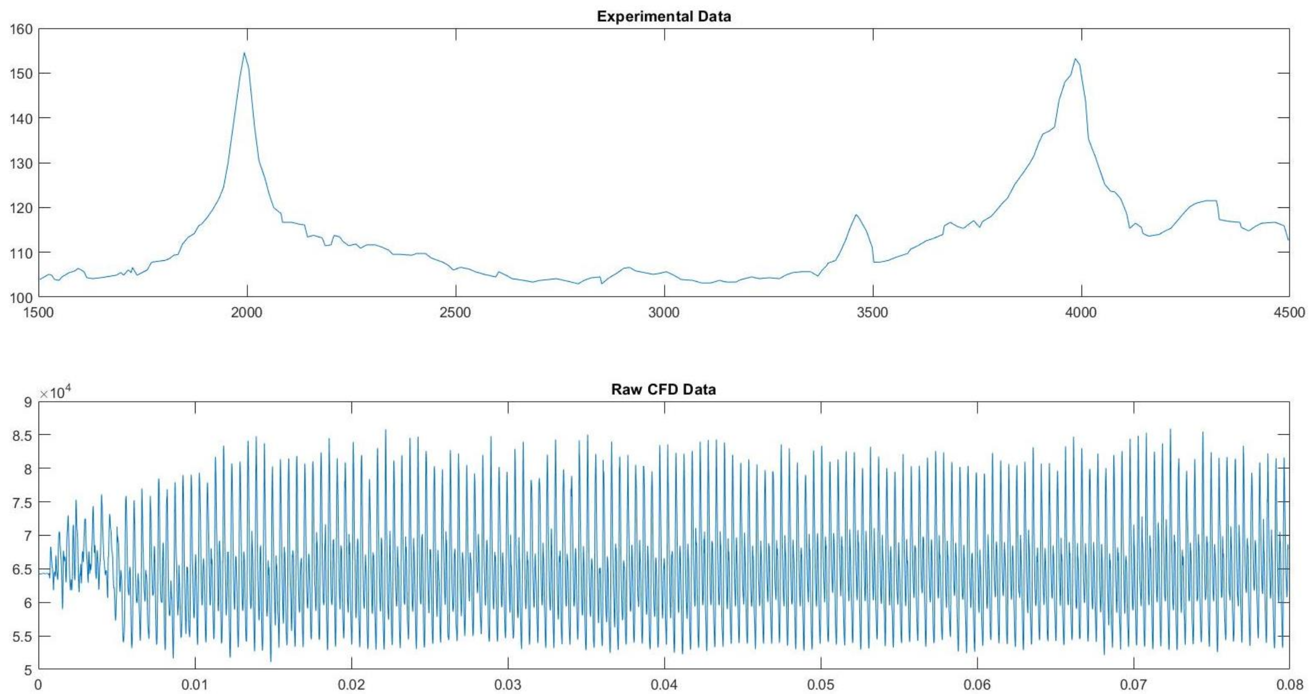

Figure 3. Direct plot of both files

As Figure 3 reveals, we need to transform the Raw CFD data into the same environment of the experimental sample. To translate the pressure signal into the frequency domain, the Fourier Transform will be required.

This process, which can be followed step by step in (Oppenheim, Schafer and Portillo, 2011), is available to be done in MATLAB with a single command “fft( )”. Remember that Fourier components travel through the real and complex plane at the same time so in order to compute it, it will be displayed its total magnitude with the function “abs( )”.Additionally, the vector of time must be also converted into frequency by computing its inverse. Then, there’s only one step left to achieve quite the same spectra in each plot.

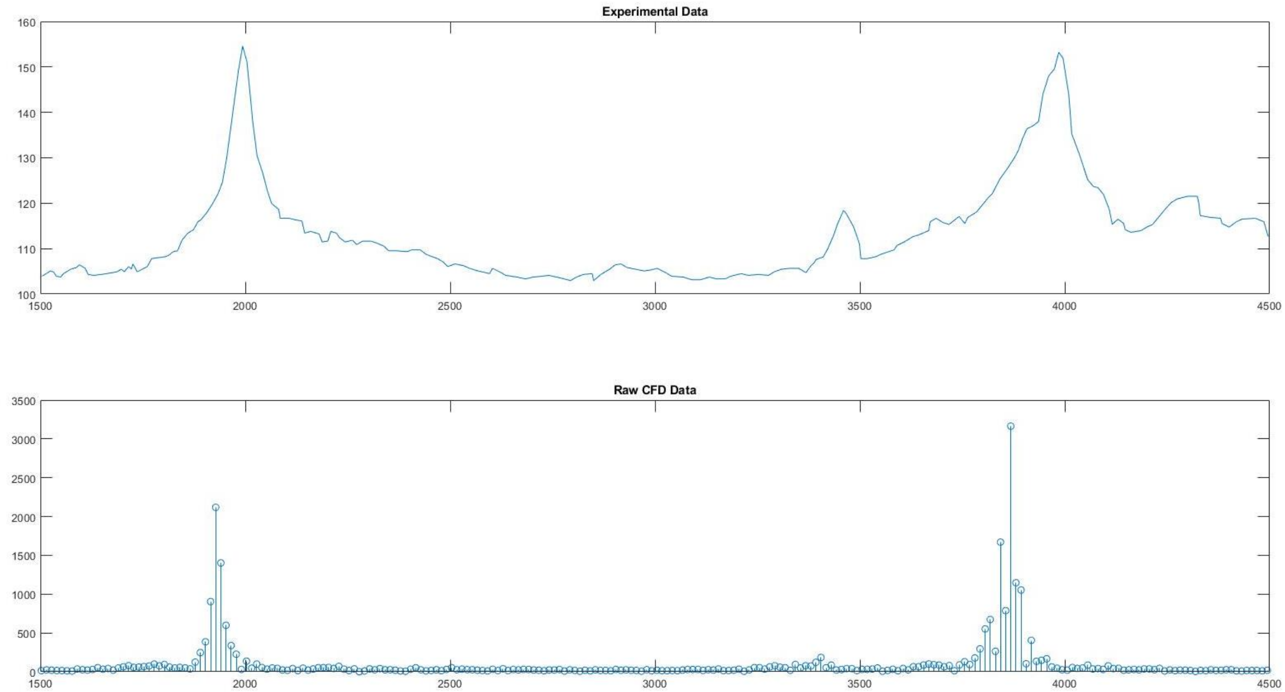

Figure 4. Experimental Data and FFT of CFD Data

Fourier transform has been graphed with the "stem function" for two reasons: to properly detect the coefficients at a determinate frequency and to locate more accurately the effects that take place.

The last remaining step to conduct is to translate the Fourier spectra into sound pressure level. To achieve this, the magnitude in "dB" will be used (note $SPL = 20 \cdot \log\left(\frac{P}{Pref}\right)$ (dB)

(1) that it is non-dimensional), which explains logarithmically the relationship between to values (usually regarding a reference value). The formula to use, then, it is the following one:

$$SPL = 20 \cdot \log\left(\frac{P}{Pref}\right) \text{ (dB)} \qquad (1)$$

Being the typical reference value $P_{ref} = 2 \cdot 10^{-5}$ as it is the usual threshold of human hearing. Finally, the plot in the same two bases is achieved in Figure 5.

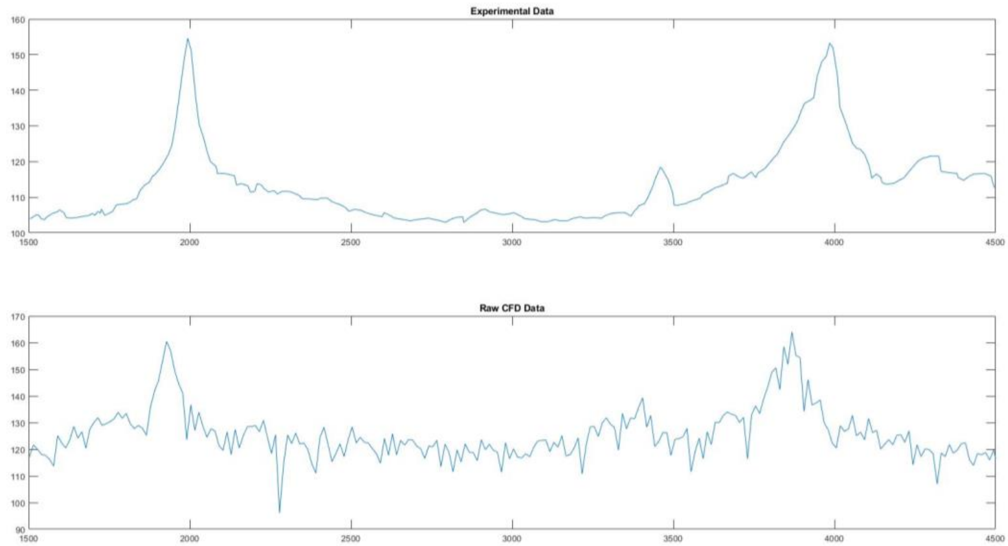

Figure 5. Experimental and CFD Data comparison

However, several differences can be seen in both. The first one (which is not that evident to see) is that there's a slight mismatch of the peaks in frequency, CFD data predicts peaks approximately 50 Hz before they happen. Furthermore, as it was pointed out, our CFD signal suffers from undesired effects, in which can be highlighted:

- **Leakage:** It is produced due to the finite windowing of the sample (usually by rectangular window). When the length of the discrete signal is not an integer multiple of the frequency, applying DFT or FFT will produce leakage. The effect that will be noted by an evident be lobation of the sample in the surroundings of the main lobe. This process can be "relatively" solved through the application off non-rectangular windows before performing the DFT.
- **Aliasing:** Seen as an overlapping of two continuous functions, once discretized by sampling, makes them indistinguishable. Hence, the original signal cannot be uniquely recovered from the discretized file (infinite signals could actually shape the discrete

one). This effect is predominant when a periodic – subsequently "sinusoidal"- function \set of functions is processed. For example, imagine we have a y=sin(4πx) function whose frequency is 2 Hz and we try to sample it with a frequency of 0.5 Hz. What we would have is the following figure:

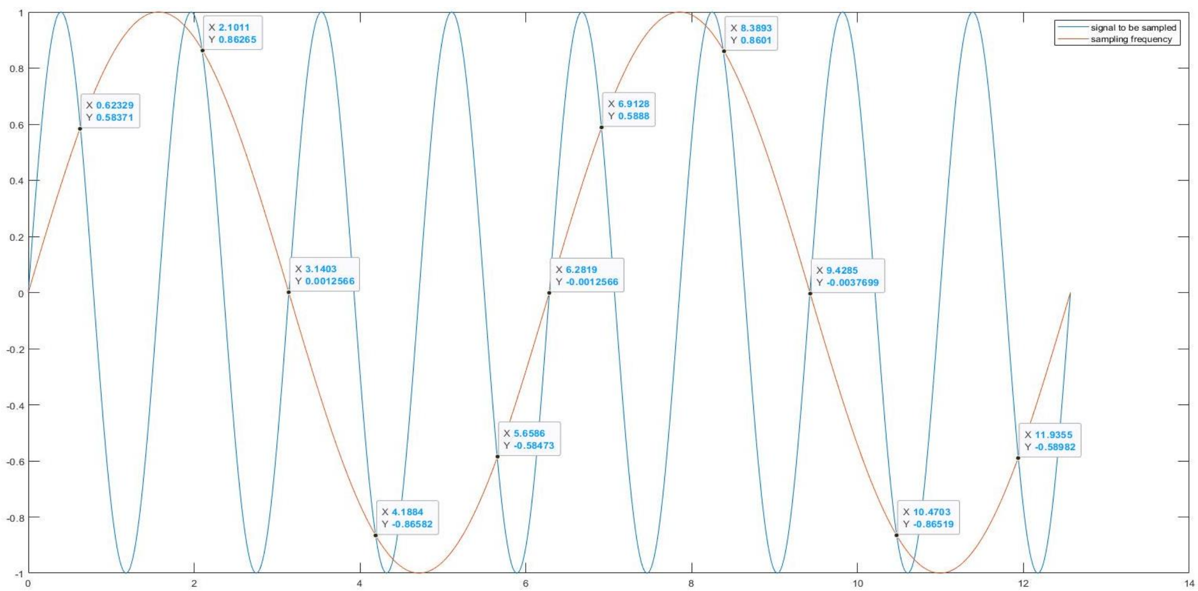

Figure 6. Signal Sampling

In this case, evidently, the original function could not be recovered. However, if we wanted to sample a function of y=sin(πx) with a frequency of 2Hz, we could definitely do it (see Figure 6 and swap the case). This happens because of the Shannon - Nyquist Theorem: "A signal can be recovered if its sampling frequency is at least twice its bandwidth". Therefore, the first step to avoid aliasing is to satisfy Nyquist Criteria by sampling at higher frequencies than double the bandwidth of the function.

By performing those methodologies, a significant enhancement should be noticed in the signal. Furthermore, it is advisable to apply high-order filters to reduce undesired contributions of high frequencies but noise as well.

Results

Prior Observations to Signal Processing

Before comparing both plots (recovering Figure 5) a proper signal processing must be done beforehand.

In terms of aliasing, not much can be done to improve our CFD signal. This is due to the fact that data is provided in an already digitalized (discretized) sort of points by a particular sampling frequency, then, resampling into higher number of samples (through interpolation) would not redound in further information of the signal. Additionally, down sampling can show better performance in peak smoothing but runs the risk of losing essential information by elimination of strategic points. However, these steps would be essential to compute if a continuous function or signal was given instead (as it can be seen at Figure 6). Nevertheless, the effect of down sampling will be studied in the following pages.

At least, there has not been any impediment to apply the most common filters in academic ambit and to conduct windowing as well. In fact, most of FIR filters encapsulate one or more windowing processes in them.

Filters

As it can be seen in (Oppenheim, Schafer and Portillo, 2011), most signals require a processing mainly based in filtering the desired information (frequencies) and reject all other contributions in the spectra, specially noise, which is present in the infinite bandwidth. Thus, particular information can be subtracted which may remain invisible otherwise.

By looking into Figure 5 it can be noticed that there are many contributions from high frequencies which add periodic disturbances. The easiest idea, then, would be to design a low-pass filter with a cutoff frequency of the maximum of our Experimental Data (4500 Hz) in order to neutralize the effects of higher frequencies. Physically, as an analogic filter, an "R-C" filter would be constructed. However, it would even be more interesting to compute a band-pass filter limited from 1500 Hz to 4500 Hz by adding another high-pass filter (then, the physical circuit would contain C-R + R-C).

Nonetheless, more efficiency can be obtained by using digital filters of high orders, some of them available in MATLAB. Here, to our CFD signal, the most known filters in the academic ambit will be applied: Simple Low-Pass Filter, Butterworth, Savitzky-Golay and Chebyshev. The properties of each filter can be viewed in more detail in (Smith,2003) and (Anon, n.d.). Additionally, the parameters managed by each filter will be shown in Appendix 3. Matlab Code .

The results from each filter have been displayed in Figure 7 and compared to the original CFD and to the Experimental curves in order to properly determine its effects and which one -in this case- provides us closer results to experimental data.

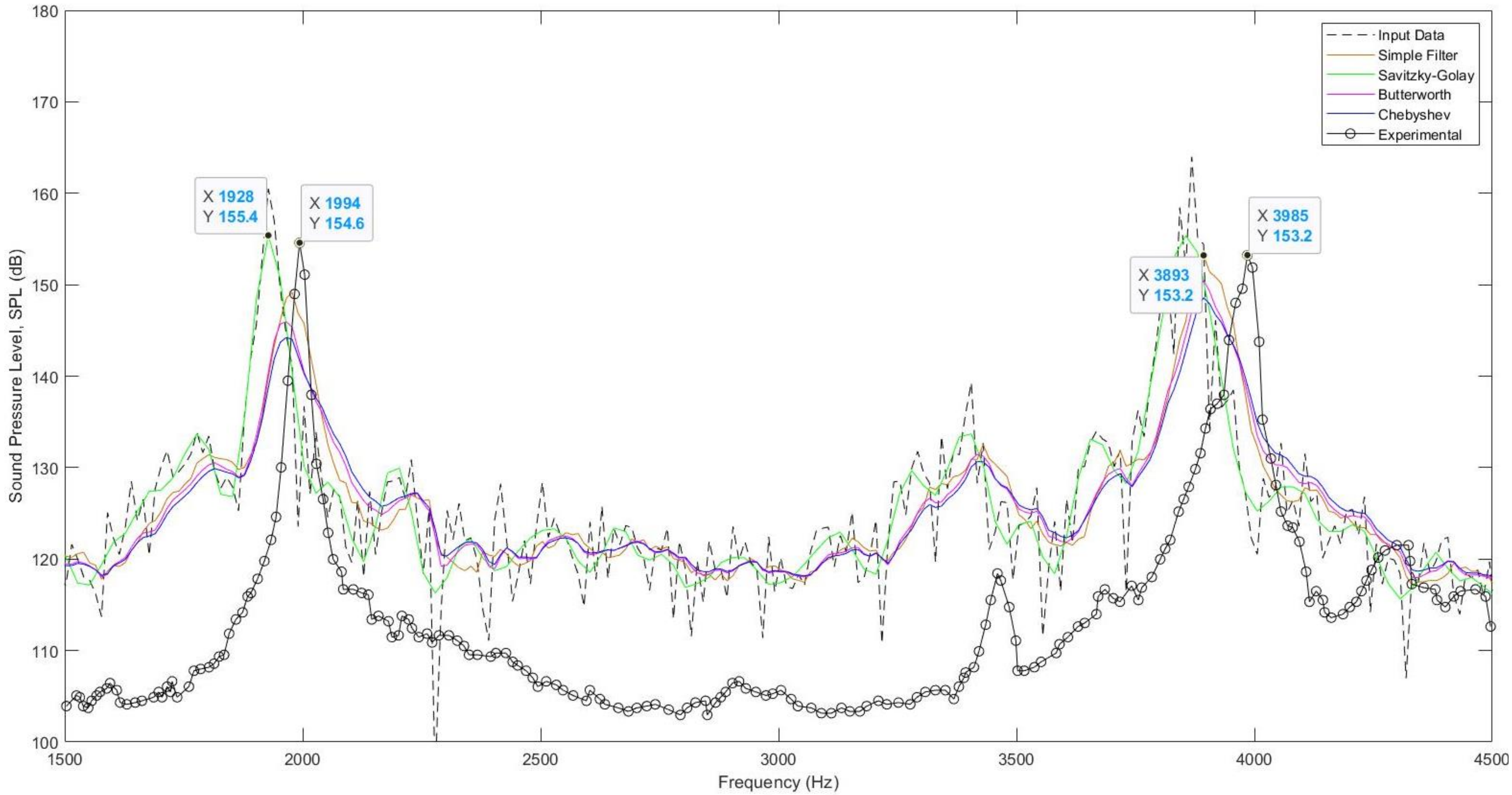

Figure 7. Filters applied to the CFD Signal

As it can be seen, most of filters perform an accurate elimination of undesired components and even some of them, eventually, overlap signal's envelope in the same value. Most of the time, their action is quite barely different from one another and so little difference can be observed. Hence, if some restricting criteria was given such as computational time, memory, etc; given their similar results the ones that satisfied those criteria should be computed.

Although, in this case, the procedures that showed more affinity to experimental were the signal filtered with Savitzky-Golay to the fundamental frequency of approximately 2 KHz and the simple low-pass filter in the environment of 4 KHz. Since it is widely recommended and normally applied as a filter and due to the great performance showed (specially in the 2 KHz main fundamental frequency neighborhood where it is extensively detailed in (Forestier, Jacquin and Geffroy, 2003)), the Savitzky-Golay may be the most interesting filter to apply.

Windowing

As it has been stated in Methodology, the application of windowing techniques to signal processing may incur in a significant enhancement of the signal quality due to the strong attenuation of spectral leakage. The visible effect of windowing is to reduce the lobation, therefore peaks get narrower and look alike straight lines (Fourier Coefficients). Nevertheless, resolution of the signal is compromised and a decrease of it can be noted.

It was said that the window should be multiplicated by the signal in time so as to then bring it to the Fourier domain and apply filters. However, by the properties of the Convolution of Fourier's Transform, the multiplication of a signal with a windowing function in time domain is equally the same as the convolution of the signal in frequency domain (see (Oppenheim, Schafer and Portillo, 2011). Due to this, our windows will be applied as weighting functions inherent in the Savitzky-Golay filter as it is usually done and recommended - according to its help guide - in MATLAB.

The evaluated window functions have been the following: Hann (normally confused with Hamming and then the *Hanning* term is unfortunately widely used), Hamming and Blackman. More information about each can be seen in the Appendix 2. Windowing Brief Theory and (Prabhu, 2014).

Once seen that the Savitzky-Golay filter is the most suitable to our case, it is applied with each windowing function to the CFD data and plotted in Figure 8.

It is revealed that, in comparison with the no-windowed filtered signal envelop, a smoothened of the signal can be obtained with any of each window. In the bigger picture, it cannot be seen, but this is due to the reduction of the lobation of the sides for each main lobe. In general terms, their performance is relatively similar since their formula is quite the same one (see Appendix 2. Windowing Brief Theory) although some erratic behavior of Blackman Window can be seen in the initial frequencies. This effect is product of the exact 0 values of the first elements of the Blackman Window Vector, then the Fourier convolution does not manage this case appropriately. Considering this little issue, it would be preferable to conduct Hann or Hamming windowing instead. Overall, the application of windows functions has led to positive results although it does not enhance signal quality to a great extent. More effect would be noted if a continuous function would be processed instead of a set of discretized points.

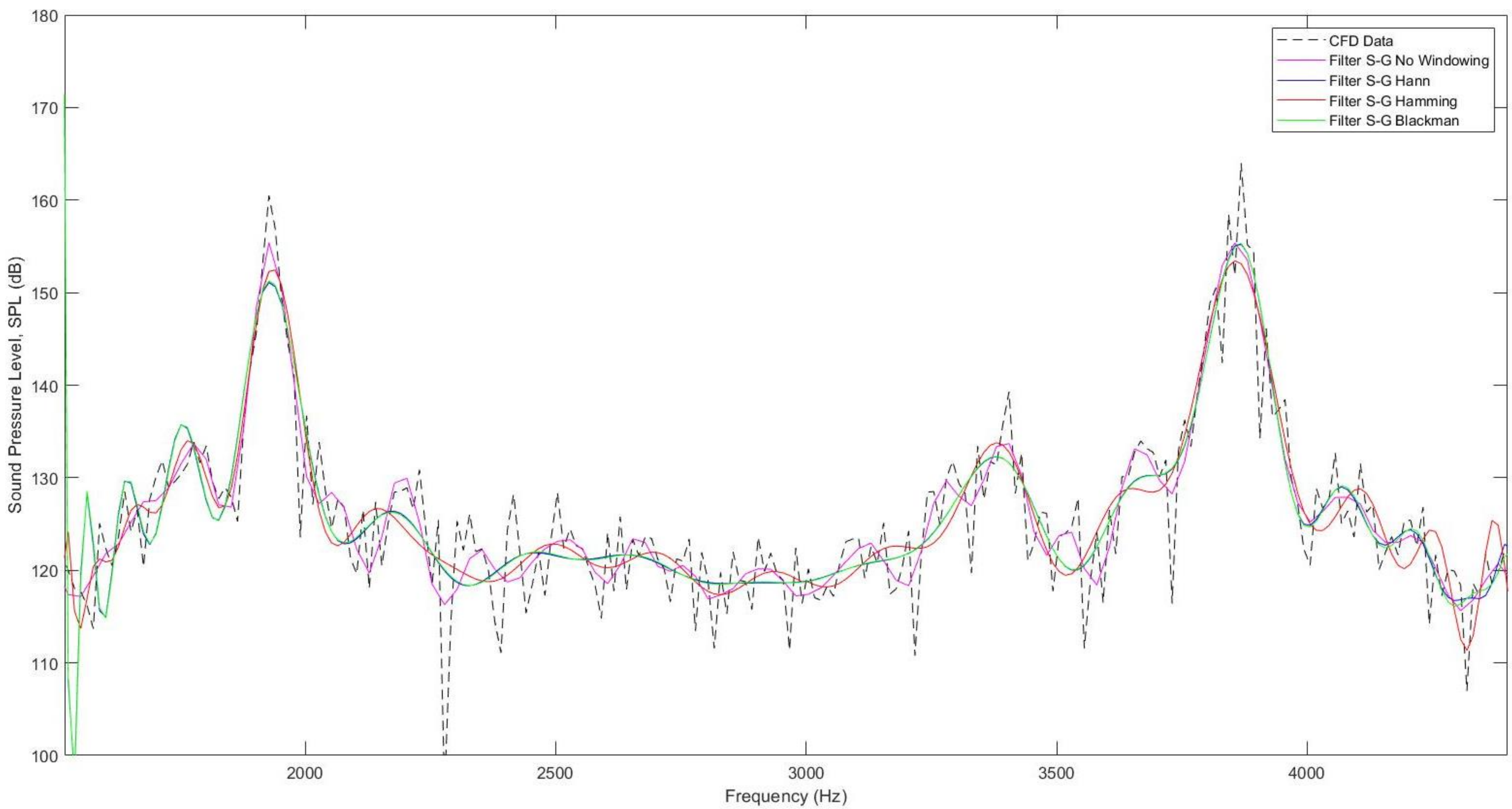

Figure 8. Windowing functions comparison

Down sampling

As it has been revealed, resampling a discretized set of points may not conclude in special benefits of our signal at all.

In the one hand, sampling at a higher frequency by applying interpolation does not provide any further information or add any interesting trait, it just enlarges our data vector and also introduces some errors as interpolated points do not have the exact value of real ones.

In the other hand, down sampling the signal to a minor sampling rate awards the danger of loosing essential information, but also might reduce the high variations of peaks in nearby points. Then, no significant improvements should be expected from this process, nevertheless, this case has been analyzed.

The original signal, once applied the Savitzky-Golay filter, has been resampled to half and quarter of points and then charted with the curve of experimental data. The CFD data vector originally includes a length of 150000 points, however between 1500 and 4500 Hz this number is reduced to 480 points. Consequently, our both functions will have 240 and 120 points respectively whilst the experimental vector contains 206.

Surprisingly, Figure 9 reveals minor enhancements in terms of peak smoothing, and the fundamental frequencies of each curve are shown. In this case, the reduction to half the points decreased its magnitude by 2 dB in 2 KHz peak, which in terms of SPL is not significant but in terms of power it decreases by a factor of 1.58 (in terms of pressure, 2.51). This corroborates the assertion that essential information is lost in the process. Nevertheless, in this particular problem, it gets closer to experimental data due to the coincidence that it had lower value than simulations.

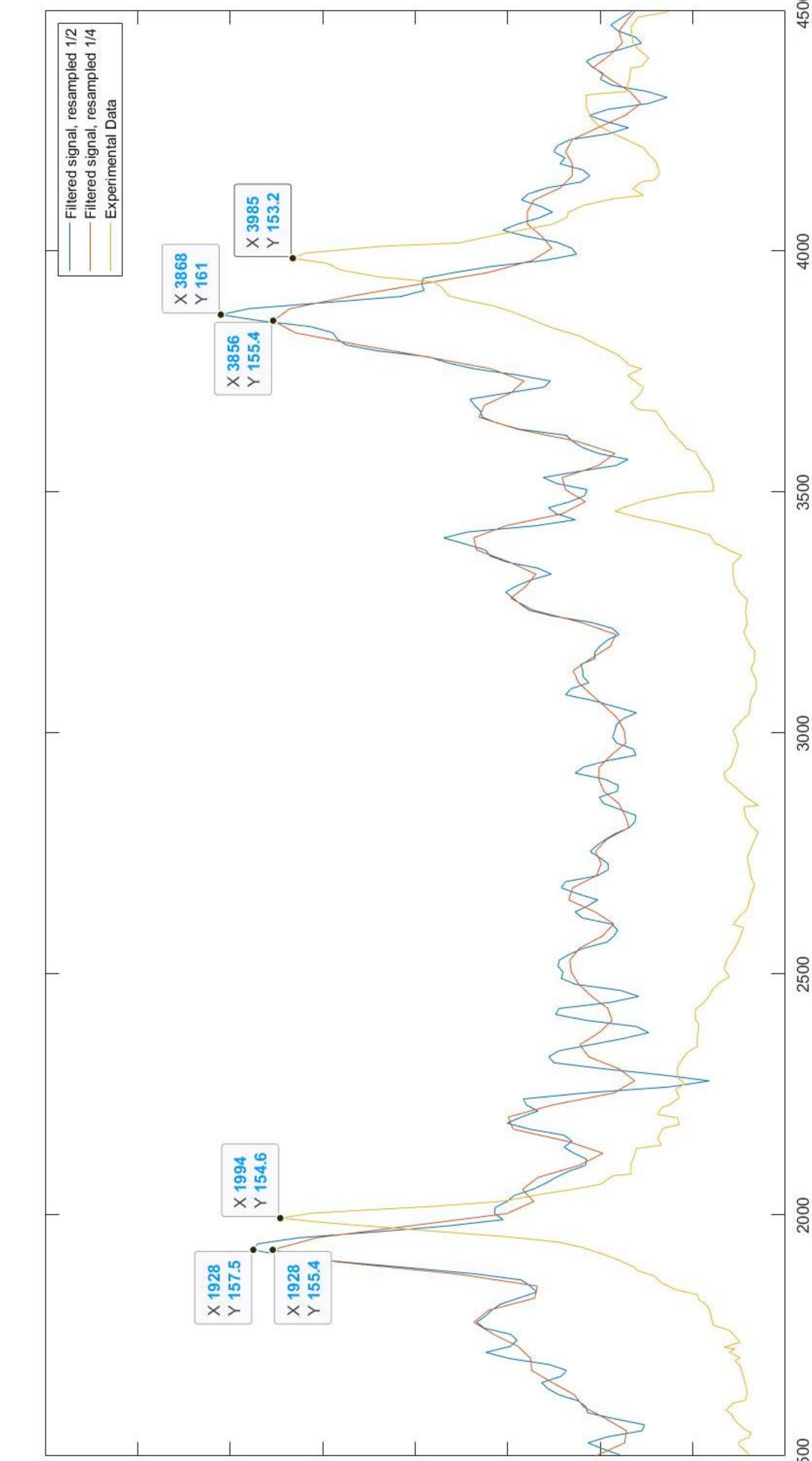

Figure 9. Down sampling effect

Conclusions

First of all, the parallel results conducted by Forestier's research and the ones obtained here will be commented. Then, the outcomes of the assignment will be discussed but also the obstacles faced in the process.

The Numerical Results obtained by CFD simulation once applied digital processing techniques show huge similarity with the experimental, as it can be seen in Figure 7, Figure 8 and Figure 9. Thus, these positive results may suggest that prediction of noise and fluid dynamic behavior can be accurately done by the numerical simulation applied. It must be considered that little differences perceived, such as the mismatch in frequency between the peaks predicted and the really obtained of approximately 70 Hz of value can be due to a large set of phenomena. As it will be discussed in the literature review, pressure can be divided into mean pressure and fluctuating pressure, and even this last term is conformed by periodic fluctuations and random fluctuations. Numerical schemes based in models are not strong in the prediction of this physical random phenomena. Furthermore, experimental data collected by transductors do not also represent the real nature of the fluid - little perturbation of the fluid is done by their physical geometry – and also undesirable effects and extern interactions are captured -such as noise- and some principles may be not. Then, the differences seen between each curves seem reasonable and satisfy the conclusions withdrawn from the research study: A fundamental frequency of 2 KHz of high intensity is sighted and corresponds to the first cavity mode (showing a great concordance with pure harmonics) as a consequence of the mixing layer phenomena.

Once verified the accurate prediction of the CFD Data, I will talk about what I have learnt in this assignment. Firstly, a great introduction to Aeroacoustics -which remained unknown to me until this assignment- has been performed by the lecture of several research papers in order to understand the experiment described in (Forestier, Jacquin and Geffroy, 2003)(Rossiter, 1964)

Later on, an understanding of the fluid behavior in cavities has been achieved. A list of general conclusions regarding the different experimental research in cavity geometries and the effects of varying parameters (L/D, M, different type of simulations) has been written in case it is needed in a near future.

Besides, valuable experience is gained in the field of data analysis and processing. In the professional ambit, it is necessary to be familiar with the methodology of how to withdraw essential information from results, specially through conducting spectral analysis and filter application. Nevertheless, it is even more important to properly know from mathematical theory which results should be expected, recognize which differences are present and its cause, and which steps should be applied to improve them. Also, when the knowledge is not enough beforehand, appropriate references and literature must be found.

Overall, I believe I have achieved a really interesting and complete learning from this assignment, specially the introduction to theory of aeroacoustics (which the literature reading has been the toughest part) and also from signal processing by using MATLAB, a software I was not familiar with.

I am aware that I have exceeded the word limit because of the MATLAB code but particularly due to the large “Literature Review”, however, I could not comment with a single paragraph the deep learning that I acquired from each document. Otherwise, I would not be satisfied with the work done. Hence, I moved all the non-essential but interesting information into the Appendixes following this section.

I hope the reader enjoys this document as much as I did when I redacted it.

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Appendix 1. Literature Review

[1] Wind Tunnel Experiments on the flow over rectangular cavities at subsonic and transonic speeds (Rossiter, 1964)

This pioneer and highly reference document elaborated when aeroacoustics were not that far developed aims to describe the nature of a low over a cavity through the analysis of the *Sound Pressure Level* (SPL), and through varying L/D and M parameters in order to see the bigger picture, the total influence of this factors into the flow and turbulence production. So as to analyze the non-stabilized obtained data, pressure fluctuations are split into periodic terms and randomly fluctuating terms.

It is found that periodic fluctuations have a close relationship with the production of strong acoustic radiation. They, somehow, seem to be produced by acoustic resonance. Those fluctuations are increased if Mach is increasing too.

The L/D (large/depth) parameter also has a huge impact on the pressure decomposition. For larger cavities, random fluctuation of pressure is the main source. When decreasing the L/D parameter, peaks in SPL appear to demonstrate the irruption of periodic fluctuations. Consequently, for L/D <1, the periodic term is the dominant and random contribution can be neglected. However, periodic fluctuating pressure can be highly reduced with the introduction of small spoilers in the front of the cavity.

[2] Acoustic Analysis of an Axial Fan (Dogruoz and Arik, n.d.)

This report is conducted to characterize the main noise sources and their causing phenomena of axial sources. It is performed since axial fans constitute the principal responsible for the acoustic contamination produced by airplanes. This noise, nevertheless, is known to be caused by flow turbulence.

The approach to model the situation has been carried out under the FW-H aeroacoustics assumption, applied to a variety of axial fans rotating at different speeds.

The analysis of the noise has been mainly spectral (SPL is quantified) such as the previous Rossiter's study and the three unsteady acoustic sources have been identified. Monopoles are negligible since fan blades are thin, dipoles are predominant, and quadrupoles can be neglected due to the subsonic flow.

The comparison between the CFD study using FW-H model and experimental data reveals that the FW-H model is accurate enough to be used as a noise predictor for problems of this same scope.

[3] ***Analysis of pressure fluctuation in transonic cavity flows using modal decomposition.*** (Liu et al., 2018)

The basic idea of this paper is to draw further knowledge on the pressure fluctuations that appear in the fluid dynamics over a cavity by applying the latest CAA (Computerized AeroAcoustics) methods: Proper Orthogonal Decomposition (POD) and Dynamic Mode Decompositions. This study has been evaluated in the transonic environment (M=1.19) with a L/D ratio of 5.

The fact that recent investigation documents published by Ahuja et al, Hamed et al, Tracy are not congruent with the effect of the Reynolds number to the main frequencies of noise generation. Thus, although the interaction between the flow structures formed in the cavity makes the comprehension of complex fluid dynamics quite challenging, there is a strong need to throw some light to this incongruence.

The results obtained by this experiment show that there is no significant influence or correlation between Reynolds number and dominant frequencies, even recirculation produced surface decreases as Re increases, Thus, Re is proven to not affect the SPL distribution. The higher peaks of SPL seen in experiments, however, may be produced due to the increment of freestream pressure or temperature.

[4] Numerical Laser Deposition on Supersonic Cavity Flow and sensor placement strategies to control the flow. (Yilmaz and Aradag, 2013)

Both authors intent to evaluate the laser energy deposited in a flow in supersonic conditions above a cavity. The POD methodology explained previously is applied in order to obtain considerably reliable conclusions from the results. The turbulence model applied in the CFD study is the k- ω standard.

As most of the literature reviewed here, the direct experimental data is represented by SPL (in dB) vs cavity distance. With this information, further investigation can be performed as it supposes a little but new step into the modelling of fluid dynamics. Overall, unfortunately, the results and conclusions have not much in common with the problem we are dealing within this document, except for the case that the experiment takes place in a cavity.

[5] Numerical Method to compute acoustic scattering effect of a moving source. (Song et al., 2016)

The objective of this investigation is to evaluate the far field acoustic pressure generated by a ducted tail rotor. The model applied is, again, the FW-H aeroacoustics approach.

Firstly, the RANS momentum equation is particularized in the problem's conditions to describe the aerodynamical effect. However, the aeroacoustic prediction will be provided by the combination of Curle's Equation, FW-H analogy and the generalized treatment of Goldstein. Hence, all this models and assumptions are completely detailed and singularized in the evaluated case.

The numerical results obtained by the modeling of rotors are supported by the analytic calculations which the reader can follow step by step.

However, we have rather focused on the aeroacoustic explanation within this document in order to know more about the original problem faced. Hence, we have noted how it is important to clearly distinguish the fluid fields of our problem since really different behavior and fluid dynamics takes place in each.

What is surprising of this paper in comparison with others is that the noise pattern (SPL) is also plotted in polar form, in order to identify any directivity or main axis of noise propagation.

[6] Direct computation of the noise radiated by a subsonic cavity flow and application of integral methods (Gloerfelt, Bailly and Juvé, 2003)

Displaying a straight relationship with our reference paper, here it is evaluated the flow behavior facing a cavity in terms of acoustic generation. The numerical methods applied to perform the simulations are the following:

· FW-H analogy

· Kirchhoff porous

· Wave Extrapolation Method (FW-H + Kirchhoff)

As most of investigation papers, the section of governing equations is done in the first pages and highlights behavioral fluid dynamics equations (Navier-Stokes), acoustic analogy, the numerical algorithm (high order algorithms by using fourth-order Runge-Kutta and Webb's Dispersion scheme) but the boundary treatment as well.

Once obtained the CFD results, the fluid field is conveniently divided into the regions:

· Far field: It has been proven that most of the radiated noise is grouped in the fundamental frequency and logically the first harmonics. The scattering that can be observed is produced by an interference pattern between incident acoustic waves and reflected, in approximately the same bandwidth.

· Near field: here, the acoustic radiation is examined so as to determine its source. However, it is not an easy procedure since three different pressure patterns interfere in the results: two coherent structures evolving in a shear layer, second vortex caused by the flow ahead the upstream edge, and finally acoustic radiation inherent in the flow.

· Mean flow: as it has been seen in our problem study (Forrestier), for transonic conditions over a cavity and a L/D ratio of 0.42, vorticity's layer thickness evolver non-linearly but can be correctly studied if it is divided into stages. Overall, the obtained results plotted show really little discrepancies with the DNS model so they can be validated. The worst-case scenario is a mismatch of the order of 1 dB.

The methods applied are compared in the conclusions section: CAA numerical methods are costly but can accurately predict acoustic radiation sources. WEM methods may be even less efficient than CAA procedures but are still able to evaluate proper interaction between CAA far field and near. However, in terms of structural analysis, it permits to decompose the Standing Wave Pattern into incident acoustic radiation and reflected, which supposes a strong advantage of this method.

[7] CFD Analysis of flow noise at tees at natural gas station (Li et al., 2018)

Although at first glance it does not seem to match with the reference paper, it has been an useful read since the carried out study uses Ansys-Fluent (software widely used in aerospace environment and in which we are supposed to expertise) to run the simulations. Additionally, a complete SPL analysis is performed so it will serve as a model for our signal processing.

The authors, in concordance with the modern industry, conduct an investigation over acoustic radiation produced by "T" pipes or commonly known as tees in gas station. Overall, main noise sources present in gas stations are:

- Electromagnetic noise
- Mechanical noise
- Fluid dynamics noise.

An extensive study of the last is driven by the theoretical FW-H acoustic approach, and LES is used as the simulation model. Additionally, Fluent software is used to run the simulations and the standard k-ε turbulence model is applied as well.

As results, spatial pressure and velocity fields are obtained in the 3-D mesh and may predict the fluid's behavior in the tee element. Graphics of the SPL spectra over frequency have been shown in order to compare the accuracy of the simulation with the experimental data obtained. Thanks to them, more features can be withdrawn than simple fluid dynamics' variables study. These results have been discussed and then summarized in the conclusions section.

One fact that really surprised me was the fact that the generated noise belong to low frequency (0-20 Hz) hence cannot be detected by ordinary human beings, but may cause harm to internal organs due to resonance.

[8] A survey on experimental and numerical studies of convection heat transfer of nanofluids inside closed circuits. (Safaei et al., 2016)

Nowadays, heat transport, efficiency is hugely investigates since minor improvements would lead to billionaire savings in industry and better performance in components and machines.

Back in 1995, it was discovered that operating nanofluids (base fluid with compound suspended particles) would ensure a better thermal conductivity. Since then, hundreds of experiments with different suspended particles and compositions have been made to achieve the best thermal transfer. However, a big restraint is that those particles may accumulate or erode the physical elements of the conduction (ducts, pipes, valves, etc.)

Thus, this document collects quite most of the investigations and experiments made in this topic but also the varied CFD simulations done (DNS, LES, etc.) Most of them have used the k-ε turbulence model and even some used Ansys-Fluent software, which will be used by us in future assignments.

The authors, according to all the investigations, even though it is demonstrated that parameters such as Reynolds number may be as relevant as the concentration of particles, conclude that there are many inconsistencies in the investigations' results. Hence, they state the need of further investigation to be made.

Overall, this document does not supply relatively valuable information of the particular problem we are facing; although it appeared in the Scopus search and I thought it would be really worth to read. An interesting fact commented is that heated cavities may ensure better thermal conductivity, but its recirculation flows are not really clear by now.

[9] Effect of Tailing-Edge Thickness on Aerodynamic Noise for Wind Turbine Airfoil (Li et al., 2019)

The Introduction of Aeroacoustic from Lighthill to K-FW-H (FW-H analogy is corrected by Francescantonio) theory is briefly commented to give a step to the aerodynamic noise sources of any airfoil. In this case, the DN97-W-300 will be evaluated. It is clearly shown that most of the aerodynamic noise will be caused by the trailing-edge source. Therefore, investigations on Aeroacoustic of Airfoils are presented as a reference for the present study, thus, obtained results will be compares to previous validated work.

The study will use three different simulation techniques: URANS (Unsteady Reynolds-Averaged Navier-Stokes), DES (Detached Eddy Simulations) and LES (Large Eddy Simulations).

The governing equations of each are introduced and detailed. Then, different regions of the whole fluid are distinguished in order to separate the efficiently study according to fluid behavior in each. Then, different assumptions will be made along the fluid field and results will largely vary in time and space. Mesh is also properly commented since it is mainly responsible for the accuracy and convergence of the solution, then, a Grid Study is conducted and validated.

As results, DES and URANS solutions are proven to be really similar, however LES results show significative deviations from both. The variable studied is mainly SPL, since it can be easily compared with direct experimental data.

[10] Measurements and Computational Fluid Dynamics predictions of the acoustic impedance of orifices. (Su et al., 2015)

This investigation tries to determine the accuracy and validation of a CFD Method (URANS) to perform predictions of impedance and other acoustic parameters in cavities of different ratio od L/D:

The choice of using URANS instead of DNS and LES is because of the high computational demand required by those other simulation approaches, although they tend to withdraw more precise results, and specially DNS, is able to deal with quite all scales. However, URANS has been proven to be really close to experimental data obtained -through a set of multi-microphones placed in different locations of the geometry- and even revealed some features that the analytic model could not provide.

Results (spatial unsteady impedance and reflection coefficients) are discussed within the different fluid field: mean flow, unsteady flow-field and orifice region. Then, a comparison between experimental and CFD data is made and it is demonstrated that URANS CFD prediction is accurate and worth to be applied to similar cases to this one. Hence, there's no need to apply expensive LES and DNS simulations if similar conditions and geometries are faced, but also states the importance in validating the approach and results.

[11] Signal Processing in Discrete Time (Oppenheim, Schafer and Portillo, 2011)

This book is a must-read literature for beginners for signal analysis and to understand Fourier Transform and its consequences, to construct Digital Filters and then it gets to deeper cases. I remember I widely used it for my undergraduate studies of Aerospace Engineering in the Technical University of Madrid, especially for the subject "Communications and networks".

The importance of this book, which I preferred to the recommended lecture of (Allen and Mills, n.d.) is the fact that it starts from the very basics, but step by step gets to deeper knowledge by constantly using clear mathematical demonstration. With the complete variety of examples -and pages- it shows the whole world of applications of the Fourier Analysis. Fourier, at first glance to beginners, may seem messy and complicated, but here it is clearly and elegantly explained. I remember I really enjoyed its reading.

Furthermore, I also recently used it to consult the windowing techniques to be applied, to refresh the Fourier Convolution properties and to select which filters may be more interesting to perform.

Appendix 2. Windowing Brief Theory

According to (Oppenheim, Schafer and Portillo, 2011), the most basic procedure to achieve to analyze digitally a signal coming from time-domain data must follow the scheme:

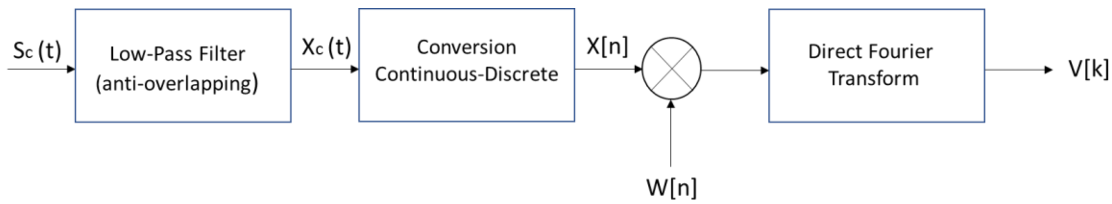

Figure 10. Signal Processing Scheme

A continuous signal $S_c(t)$ enters into a low-pass filter step that integrates oversampling, low-pass filtering and decimating processes. Secondly, the output time signal $X_c(t)$ is discretized by an Analogic/Digital Converter, but this step can also be implicitly done by the sensor that primarily captures the signal.

Then, since signal is not infinite, it is recommended to apply windowing techniques before performing the DFT to prevent spectral leakage as a result of the side discontinuities in the finite signal. Afterwards, the DFT is completed and the signal is ready to be finally conveniently processed.

Here we will detail some main characteristics of the windowing functions applied in the document. This theory has been extracted from: (National Instruments, n.d.; Oppenheim, Schafer and Portillo, 2011; Prabhu, 2014; Smith, n.d.)

- **Rectangular:** along the interval of the sample, the window function possesses a unitary value, then discontinuities in the limits will be expected. If we do not apply other windowing functions to our sample, then, our signal will suffer from this case. If we run the next code in MATLAB we will see the problems of rectangular windows

```
L = 64; wvtool(rectwin(L))
```

Then, the following figure will be obtained:

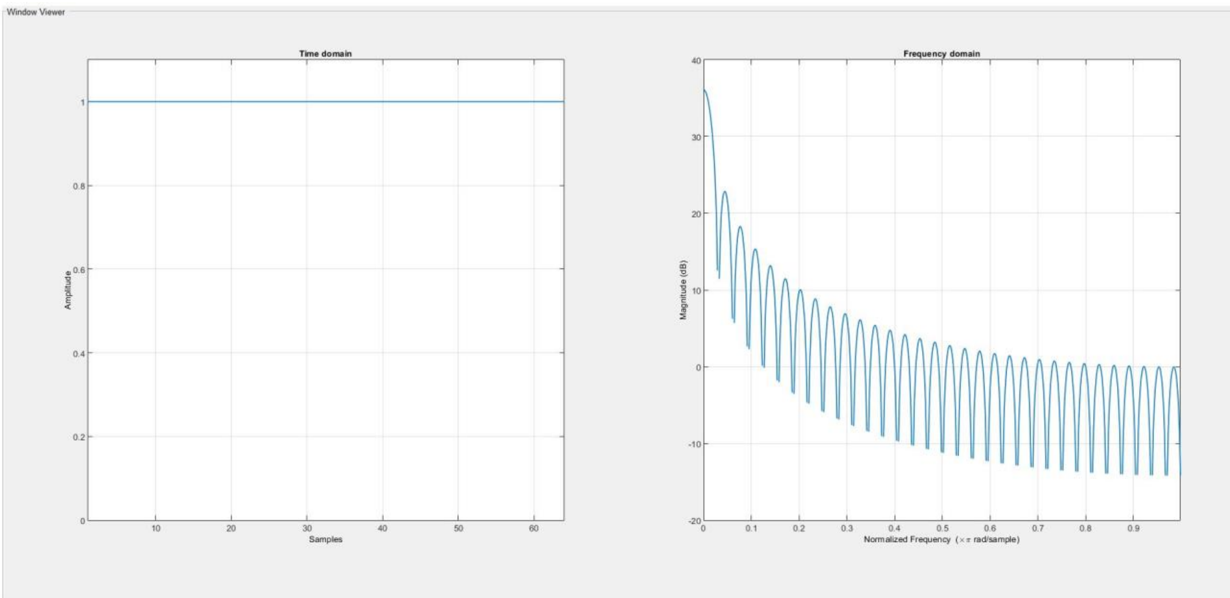

Figure 11. Rectangular Window: Time and Frequency Domain

As it can be noted, in the Fourier Domain it possesses side lobation with significant magnitude next to the fundamental peak. Physically, they should not exist, hence the importance of reducing this effect with the application of windowing techniques.

- **Hann Window**

It is the most used window to carry a smoothing of the discontinuities present in rectangular (predetermined) windowed signals – consequently, all finite signals- especially with audio processing. It is simply a sinusoidal function (see Equation 2) which, convoluted with the spectra

$$w(k) = 0.5 \cdot \left(1 - \cos\left(2 \cdot \pi \cdot \frac{k}{n+1}\right)\right) \ \forall k = 1, \dots, n \qquad (2)$$

Equation 2. Hann Window function

If it is analyzed with the MATLAB software, through the example code:

```
L = 64; wvtool(hann(L))
```

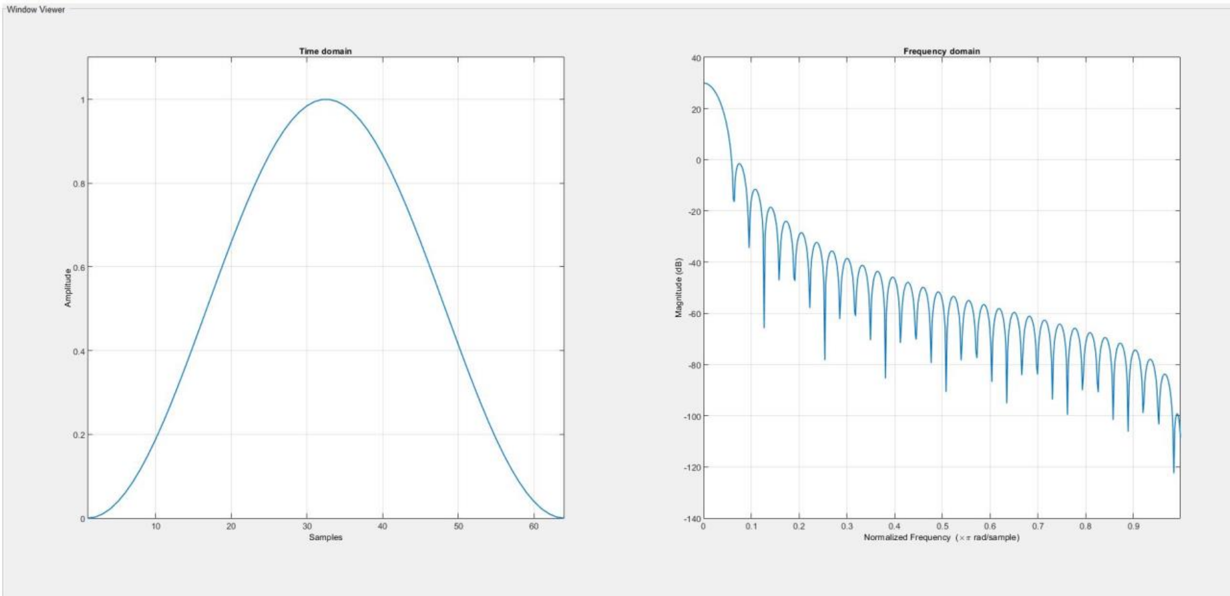

Figure 12. Hann Windowing spectra and its half – symmetrical Fourier Transform

From which a decent side-lobe attenuation in the Fourier Transform of the signal – in comparison with the Rectangular Window- can be noted.

- **Hamming:**

Like the Hann window as it can be noted by Hamming's function (see Equation 3. Hamming Window Function), it is also a sinusoidal window.

$$w(k) = 0.54 - 0.46 \cdot \left(\cos\left(2 \cdot \pi \cdot \frac{k}{n-1}\right)\right) \;\; \forall k = 1, \dots, n-1 \qquad (3)$$

Equation 3. Hamming Window Function

In contrast, whilst in Hann window both limits reach the 0 value to eliminate all discontinuity, in Hamming window they do not, then a slight discontinuity in both limits can be perceived. Then, it performs better in reducing the nearest side lobe of the fundamental lobe but looses efficiency in the rest of the spectra. According to:(National Instruments, n.d.), these differences can be seen in the following image:

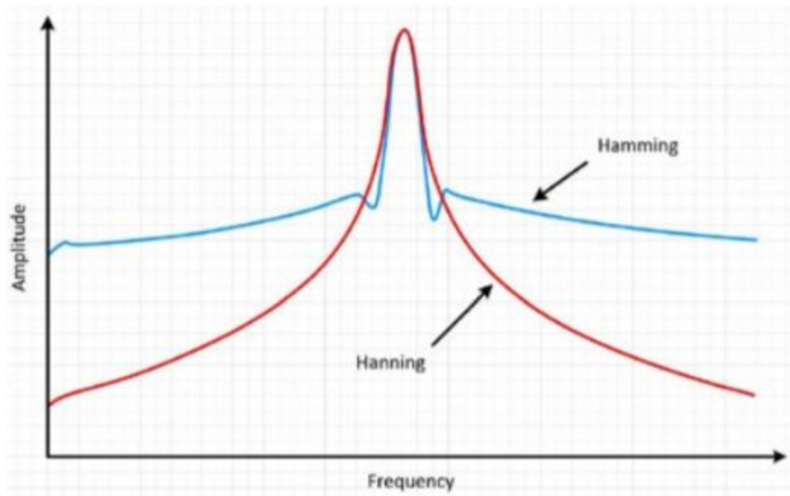

Figure 13. Comparison between Hamming and Hann Window spectra. Source: (National Instruments, n.d.)

Again, Matlab is able to run the Hamming windowing with a single function with the example code: L = 64; wvtool(hamming(L)) for a sample of 64 points.

All the conclusions stated can be corroborated by running the previous code and looking into Figure 14, where the side lobation is evidently great nearby the fundamental peak but increases along frequency.

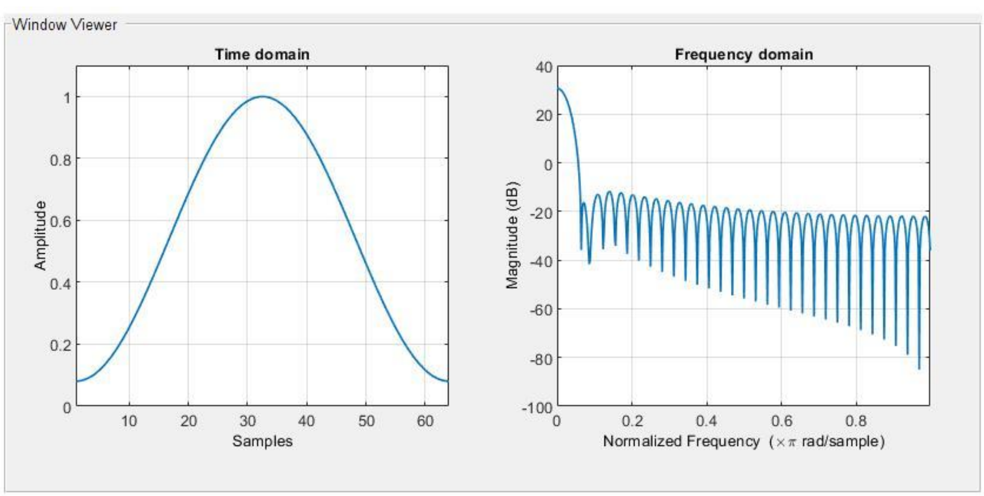

Figure 14. Hamming Windowing spectra and its half – symmetrical Fourier Transform

· **Blackman Window:**

Like Hann and Hamming window, it is also formed by a sinusoidal function, nevertheless in this case, it contains two cosines:

$$w\,(k) = 0.42\ -\ 0.5 \cdot \cos\left(2 \cdot \pi \cdot \frac{k-1}{n-1}\right) + 0.08 \cdot \cos\left(4 \cdot \pi \cdot \frac{k-1}{n-1}\right) \qquad (4)$$

Equation 4. Blackman Window Function

Consequently, when plotted in Figure 15 - in comparison with Hann and Hamming window- the spectra of the signal will have wider-peak lobation but the presence of parasite frequencies is lower than those two other functions.

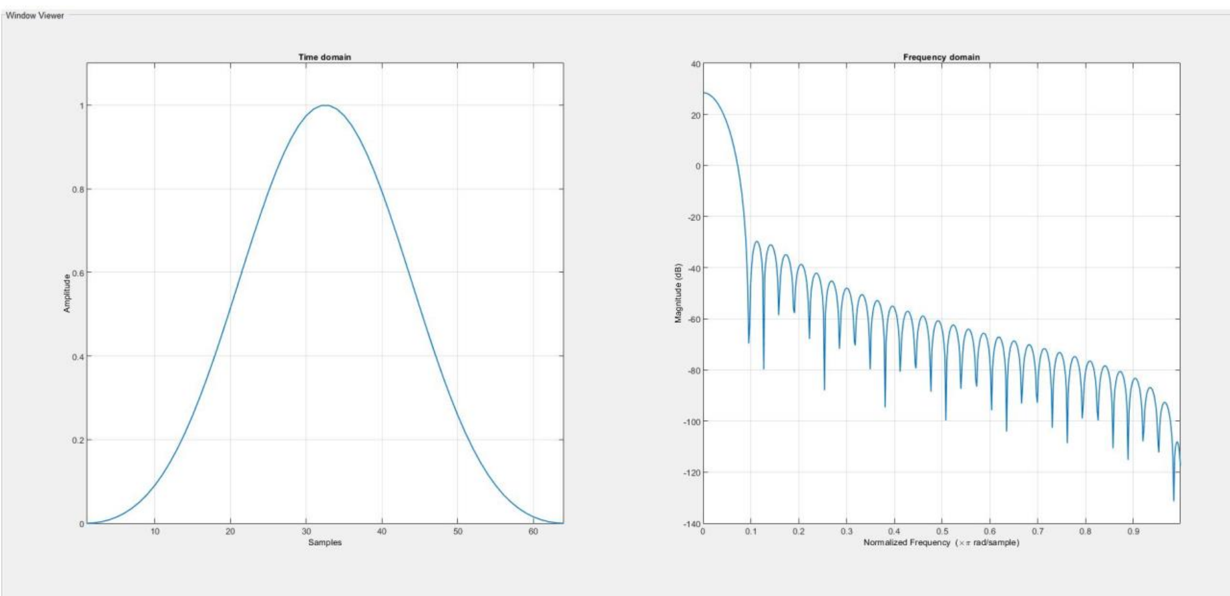

Figure 15. Blackman Windowing spectra and its half – symmetrical Fourier Transform

After all, there's not a clear better window function. The choice must rely on a compromise solution according to each one's properties, nevertheless, between Blackman, Hamming and Hann no much significant difference will be obtain. Thus, most of times -probably due to its simplicity and good performance – Hann function is the one applied.

Then, there's only a general comparison between all of them left to be made.

According to (Anon, n.d.), the representation of each's spectra:

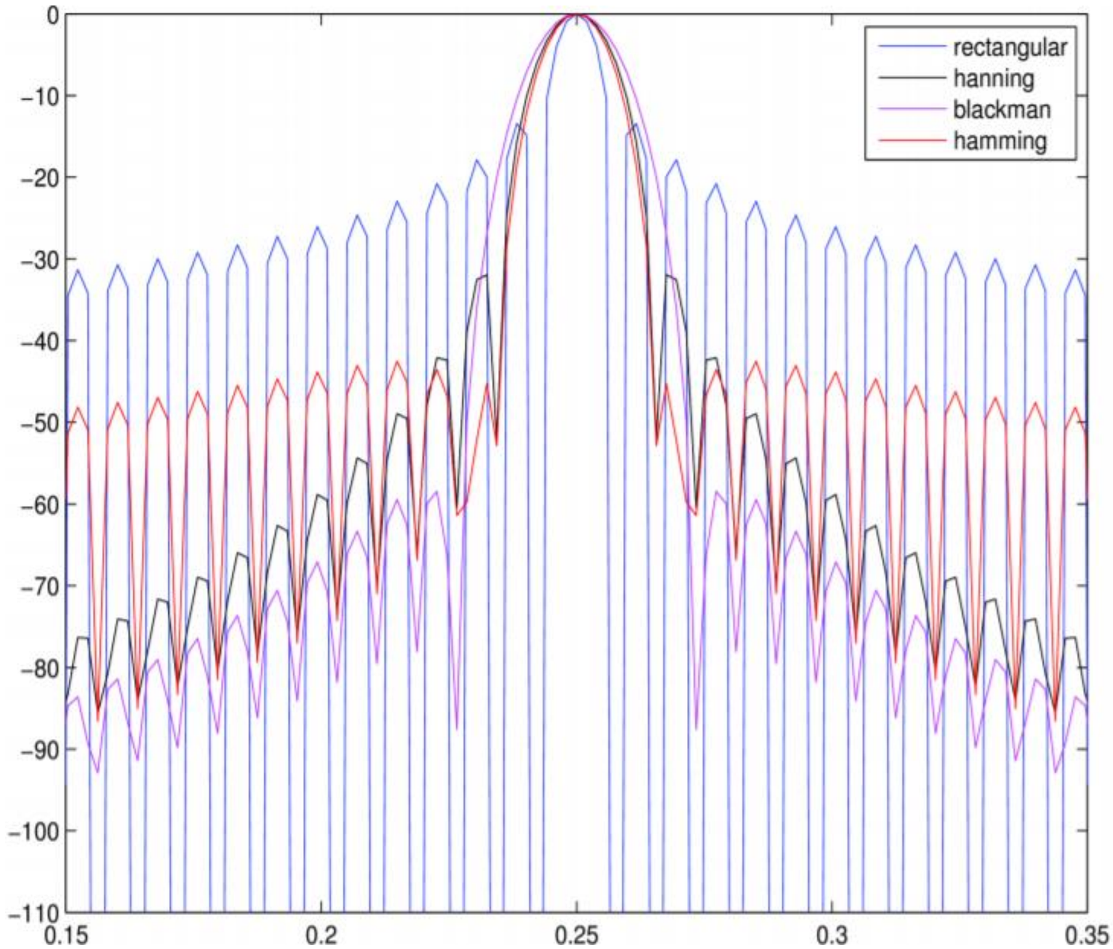

Figure 16. Spectra for the evaluated windowing functions

Then, if we consider an example function $y = cos(2\pi \cdot t) + noise$; being noise modeled in MATLAB with the random function "rand(length(t))", and we evaluate it from 0 to 0.1 with

1001 points between, the window amplitude (time domain) in *Figure 17* and its convolution (effect) once applied to the signal in frequency domain in Figure 18.

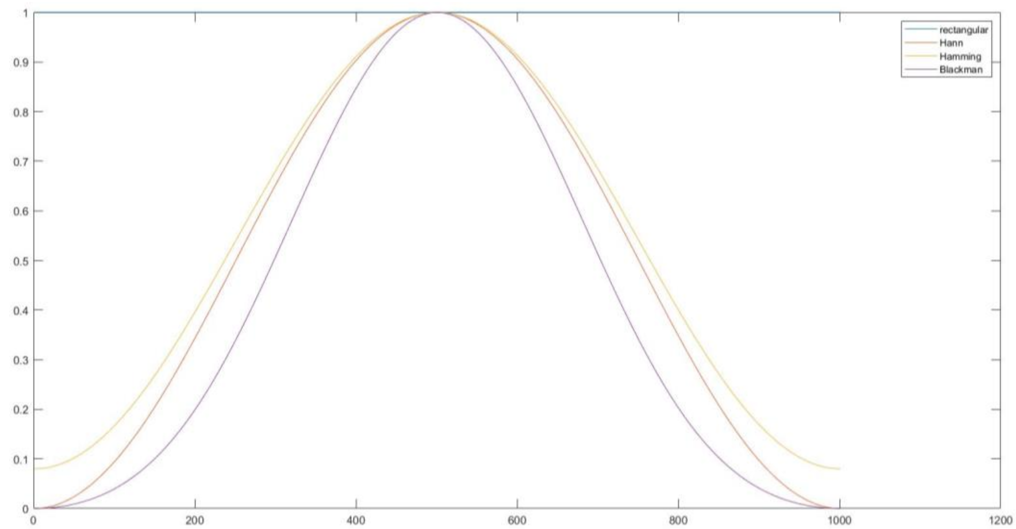

Figure 17. Time domain Envelope of Windowing Functions

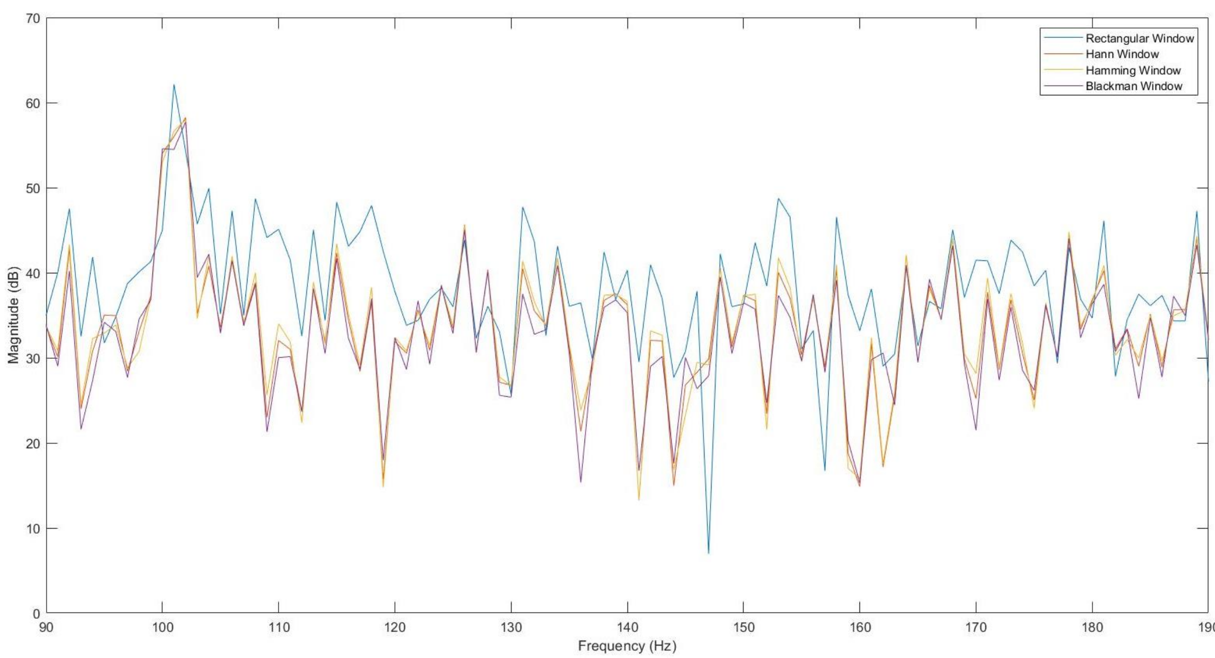

Figure 18. Windows applied to the continuous function – frequency domain

Finally, Figure 18 reveals the similar behavior of Hann, Hamming and Blackman windowing and how they result beneficial in terms of discontinuity eliminations compared to the rectangular window. It must be said again that, not applying windowing to out signal is exactly the same as the rectangular window.

Appendix 3. Matlab Code

```
% Assignment 2 Marc Barcelo
clc
clear all;
format long;
exerc = importdata('pressure_raw_cfd.dat');
N = length(exerc(:,1));
T1 = zeros(N,1);
D1 = zeros(N,1);
T1 = exerc(:,1);
D1 = exerc(:,2);


for i=1:N-1                  % Calculation of mean freq - 
creation of vector
    meanT=T1(i+1)-T1(i);
end;


FS=1/mean(meanT);            % Sampling freq

%% FIRST RESAMPLING
FFT1=fft(D1);
P12=abs(FFT1/numel(D1));
P11=P12(1:(numel(D1)/2)+1);
SPLDB=20*log10(P11/(2e-5));
F1=FS*(0:(numel(D1)/2))/numel(D1);

%figure
%plot(F1, SPLDB )
%xlim([1500 4500]);
%ylim([100 180]);


%% Filter Savitzky-Golay
filtersg   = sgolayfilt(SPLDB,38, 61);
%% Filter Butterworth
order=1;
wc=2*pi*20000/FS;
[b,a]=butter(order,wc,'low');
x_but=filter(b,a,SPLDB);

%% Filter Chebyshev
```

```
[b,a]=cheby1(1,4,wc,'low') ;
x_cheb=filter(b,a,SPLDB);
%figure('Name','cheb','NumberTitle','off');
%plot (F1,x_cheb); title ('Filtered Signal');
%xlim([1500 4500]);
%ylim([100 180]);

%% Filter Savitzky Golay + RESAMPLING
fsResamp=938887;
FS=1877774;
 [p,q]=rat(fsResamp/FS);
VResamp=resample(SPLDB,1,2);
F2=fsResamp*(0:(numel(VResamp)-1))/numel(VResamp);
vAvg=sgolayfilt(VResamp,38,61);

%figure('Name','Comparison Filtered Resample x2 - Filtered
Resample x4','NumberTitle','off');
%subplot(2,1,1)
%plot(F1,[SPLDB,filtersg])
%xlim([1500 4500]);
%ylim([100 180]);
%subplot(2,1,2)
%plot(F2,[VResamp,vAvg]);
%xlim([1500 4500]);
%ylim([100 180]);

%figure
%plot(F1,filtersg, F2, vAvg)
%xlim([1500 4500]);
%ylim([100 180]);

%% Import Experimental Data + Comparison with S-G filter
and S-G filter with resampling

experiment = importdata('pressure_experiment.dat');
N = length(experiment(:,1));
F = zeros(N,1);
SPL = zeros(N,1);
F = experiment(:,1);
SPL = experiment(:,2);

figure
subplot(2,1,1)
plot (F(:,1), SPL(:,1)), title('Experimental Data')
```

```
subplot(2,1,2)
plot(T1,D1);title('Raw CFD Data')

figure('Name','Comparison Filtered Resample x2 - Filtered
Resample x4 + Experimental','NumberTitle','off');
scatter(F1,filtersg)
hold on
scatter(F2, vAvg)
hold on
scatter(F(:,1), SPL(:,1))
xlim([1500 4500]);
ylim([100 180]);

%% Simple Filter

windowSize = 8;
b = (1/windowSize)*ones(1,windowSize);
a = 1;
y = filter(b,a,SPLDB);

%% All filter comparison

figure('Name','Another Filter');
plot(F1,SPLDB, 'k--')
hold on
plot(F1,y,'color',[202, 104, 0]/250 )
hold on
plot (F2, vAvg,'g')
hold on
plot(F1,x_but,'m')
hold on
plot(F1,x_cheb,'b')
hold on
plot(F(:,1),SPL(:,1),'k-o')
legend('Input Data','Simple Filter', 'Savitzky-Golay',
'Butterworth','Chebyshev', 'Experimental')
xlim([1500 4500]);
ylim([100 180]);

%% Shortening vectors
Fb=F1>=1500 & F1<4500;
xs=F1(1,Fb);
xs=xs';
ys=SPLDB(Fb);
```

```
Fb=F2>=1500 & F2<4500;
F2=F2(1,Fb);
vAvg=vAvg(Fb);


%% Windowing  + Filter

figure
 plot(xs,ys,'k--');
 xlim([1520 4400]);
 ylim([100 180]);
 hold on
 plot (F2, vAvg,'m')
 xlim([1520 4400]);
 ylim([100 180]);
% Hann
  w=hann(239);
  w(1)=w(2);
  w(239)=w(230);
  ysh= sgolayfilt(ys,41, 239,w);
 plot(xs,ysh,'b')
  xlim([1520 4400]);
 ylim([100 180]);
 hold on
 %Hamming
  w=hamming(239);
 yshm  = sgolayfilt(ys,41, 239,w);
 plot(xs,yshm,'r')
  xlim([1520 4400]);
 ylim([100 180]);
 hold on;
 %Blackman
  w=blackman(239);
  w(1)=w(2);
  w(239)=w(230);
 ysb  = sgolayfilt(ys,41,239,w);
 plot(xs,ysb,'g')
 xlim([1520 4400]);
 ylim([100 180]);
 legend('CFD Data','Filter S-G No Windowing', 'Filter S-G
Hann ', 'Filter S-G Hamming','Filter S-G Blackman')
```