Thermal Turbomachinery - Laboratory exercise
(MJ2430)

Measurements of Loading of a Turbine Blade Cascade

Author :
Valentin Duvivier

Encadred by :
Jens Fridh
Silvia Trevisan

March 6th 2020

1 Introduction

The main objective of this experiment was to study the variations of the aerodynamic loading over different variables such as the inflow speed and the inlet angle.

The purposes were to show and quantify those influences, both for a steady and an unsteady loading. For this last point, we will see that the purpose was rather to see its physical interpretation with regard to the steady loading and its fluctuation over the shape's location studied.

Finally, we gathered the informations post-processed after the experiment in order to respond to the objectives discussed above.

Throughout this report, you will see that the main method used for the steady part is the PI theorem. This method will consist in defining the coefficient α and in the following equation :

$$Aero\ loading = Cst * Frequency^{\alpha} * Angle^{\beta} \tag{1}$$

Indeed, we want to know if there is a dependence from the loading over both the frequency and the angle. This method allow us to make this assumption and to subsequently quantify these influence, by getting the values for the factors α and . The "Cst" term is supposedly gathering the other terms that the loading would depend on (inflow fluid volumic mass, viscous friction coeff, etc), but because we keep them constant during the study (mainly by considering a unique incoming fluid), we denote them by a constant term (= Cst).

We will split this method into 2 parts :

— the first one where we will determine α, plotting the function log(Aero loading) = α*log(Frequency) + b ; which implies that we take a look to the influence of the frequency by keeping the angle constant. We decided to display the results for **angle = 20** but the results for other angles can be found using the Matlab code in link.

— the second one where we will determine β, plotting the function log(Aero loading) = β*log(angle) + b ; which implies that we take a look to the influence of the angle by keeping the frequency constant. We decided to display the results for **frequency = 15**.

As a conclusion, we will make the balance sheet on the informations we got thanks to this lab seance and the subsequent post-processing. It will be the occasion to make the link both numerically and visually between the steady and unsteady aspects of the pressure.

1.1 Objectives

For the first part, more than quantifying the dependence with respect to the two variables, the point will be to compare the data to then conclude on which aspect influences the most the aerodynamic loading. This is why we will often compare different diagram even if we try to avoid that to the maximum to simplify the post-processed data's exposition.

In a second time, we will be aiming to study the unsteady part of the loading and to build errors bands from it as we will see that the unsteady pressure is equivalent to a range of fluctuation for the steady part.

1.2 Material and system

Throughout the study, we managed to make 9 experiments : 3 at different angles with 3 different frequencies for each.

We made those experiments for several blades but we are only looking to the five on the middle as they are the only one to have sensor to measure the loading. They have indeed 15 sensors each, at the same location, that aim to give the loading of the blade.

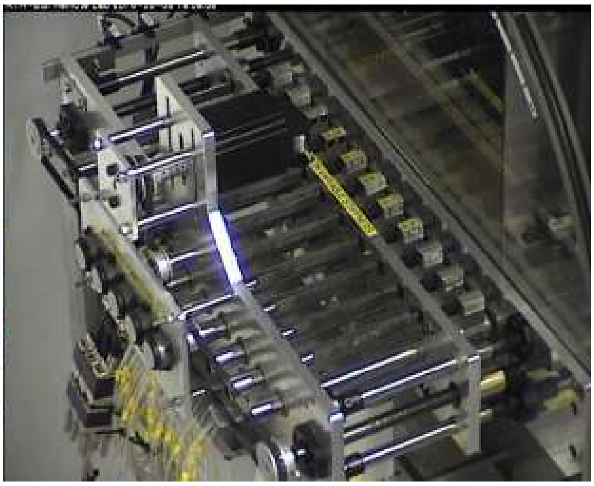
Furthermore, we will often been considering only the blade b0 to then extrapolate the results to the general behavior of the blade in a flutter lab. Indeed, even if we will still analyse the other blades' loading, to take a deeper look into a specific example will facilitate the report, in term of figures displayed, as well as the post-processing in general.

This big assumption will then aim in simplifying the results presented here. It will be up to the reader curiosity to check for the results of the other blades. Below, we are summarizing the assumptions that are being taken :

— Blade b0, angle = 20 to analyse the dependence in frequency [10 15 20]

— Blade b0, frequency = 15 to analyse the dependence in angle [10 20 30]

Here is a sight of the experimental apparatus :

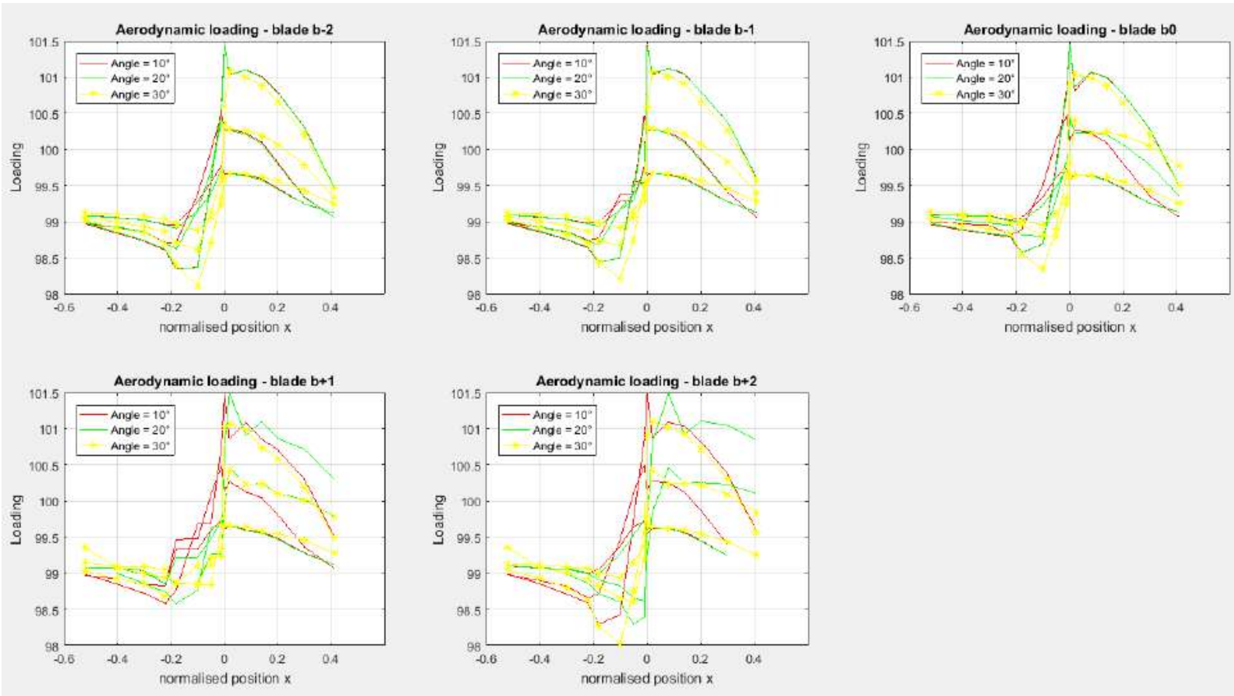



2 Steady Loading

In this first part, we are willing to test the theory seen during the lectures. More specifically, we will see the aerodynamic loading through experiment that will permit us to get a better hindsight on how the loading behaves depending on our problem's data.

We will first compare the loading in each point before trying to quantify it, using mainly Matlab, for which the code is in link.

First, we have here a graphic for the 5 blades having taps, and we considered the loading for each one the 15 sensors :



To sum up, we have plotted for the three blade the 9 experiments, and we are looking to the global shape of the loading. We note that each line of the same color represents an experiment at the same inflow angle.

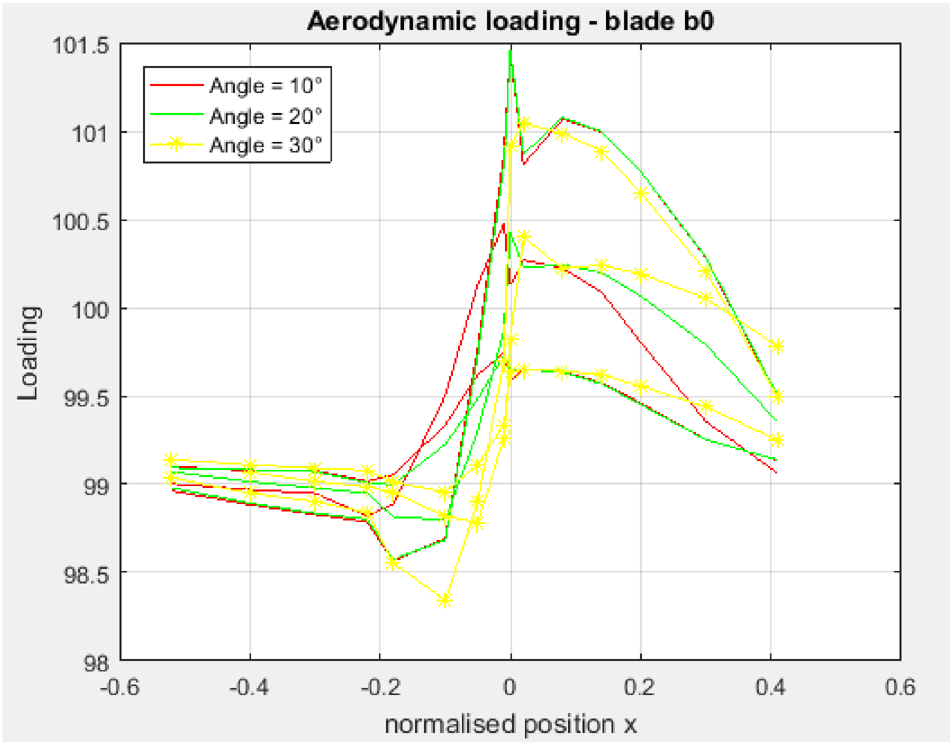
First, we see that the blades look all to have the same shape. This observation denote the frequency for the blade : is the shape of the loading constant for each blade ? We see here, that the global shape of the loading is constant within each scheme but also when considering the five blades.

Nevertheless, even though it is difficult to know what is associated to uncertainty and what is due to "blade's dependence", we can see that for the blade going from b-2 to b+2, we have a little increasing of the loading. Indeed, when looking to the two last graphs, it is clear that the pressure is increasing for the pressure side while it is decreasing a bit for the suction side. All in all, these changing, even if low, have impact on the overall loading.

It would be necessary to have more cases of blade to make deeper conclusion from the graphs, but this first sight give us information on the fact that the loading might for instance depend on the location of the blade in the raw.

Besides, an even more explicit aspect shown here is that the loading is depending on either the angle and/or the frequency.

To truly understand how the loading is being influenced, we are considering the following diagram that consider only the blade b0 :



We see that for each angle, we have 3 groups of loading. It looks like it is the frequency that has the most of influence on the loading as the amplitude of the loading is apparently increasing with the frequency increasing. We thence apparently have three groups of loading, one for each frequency.

Otherwise, the shape of the loading doesn't looks to be changing with either the angle or the frequency, which would imply that this is the blade's shape that denote the blade's shape of load.

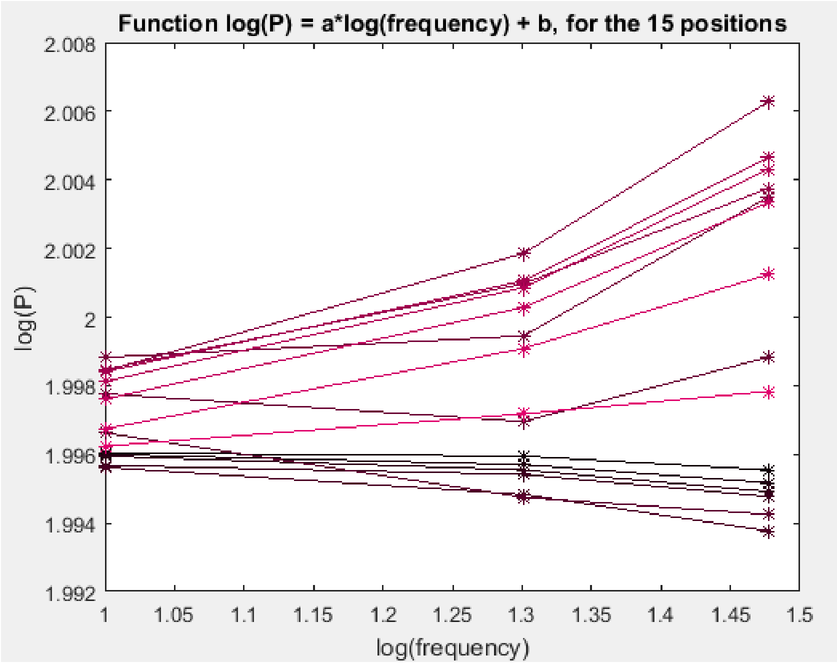
We will anyway take a deeper look to it and see if these rough observations appear later on the post process.

2.0.1 Influence of the frequency (= Mach Number)

We recall that we are in this part looking to the equation :

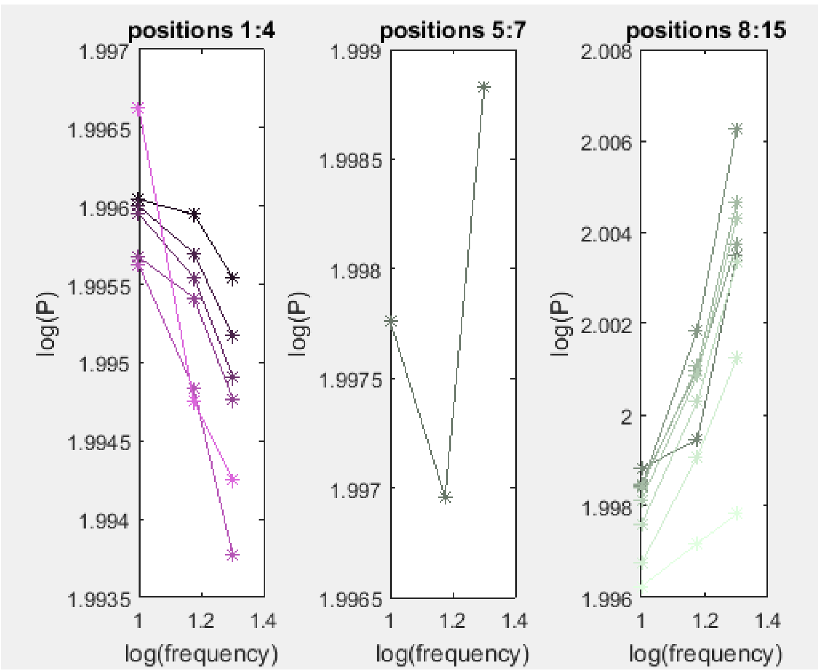
$$log(Aero\ loading) = \alpha * log(Frequency) + b \tag{2}$$

On the Matlab code, this Part is the third one and on the following diagram it looks like the slopes associated with the frequency might imply an important dependence :



Anyway, that the dependence is big or not, it is clear on this figure that the dependence depends on the considered points as the slopes are not all the same. In fact, we would expect lines that have all the same slope if the dependence wasn't varying on the blade's location. The fact that the slopes are different tend to make us consider a study being influenced by the taps' location.

To make sure of it, we decided to split this diagram considering ranges for the points. For instance, we have been plotting for the points 1 to 5 to see if they had the same slope, etc. By doing so, we went with the following diagrams splitting the points in two groups regarding to their slope :



Note : the slope on the middle shows the point (here 7) at which the transition is operating. We thus have a transition in the dependency close to the leading edge. Besides, the other transition point is made at the trailing edge as the points 15 and 1 have different dependence. It is now clear that depending on the sensor's position, the dependence won't be the same. This implies that the type of dependence will differ :

— a negative slope implies a relation of inverse proportionality

— a positive slope implies a relation of proportionality

Nevertheless, the fact of having one positive and one negative slope doesn't necessarily imply that the dependence is lower in one or the other case. We will thus calculate the slopes to then compare the intensity of each one and then conclude on how the frequency influences the aerodynamic loading.

In the following table, we summarized the values of these slopes :

Angle / Sensors' position	1 :6	8 :15
20	-0.0041 **-4.1*10e-3**	0.0175 **1.75*10e-2**

We can now make some conclusion regarding to the frequency :

— The order of dependence of the frequency is of order 10e-3 to 10e-2 ;

— The influence changes of type (inverse proportionally to proportionality) and of intensity. Regarding this last point, we don't do any sharp conclusion on it as it may have been subject to errors and we could easily consider that the variations enter within the range of uncertainty.

These results lead to this generalised equation for the dependence on frequency :

$$Aero\ loading = Cst * Frequency^{\pm 10e-3} \tag{3}$$

This dependence in frequency has also to be associated with the one in speed for the incoming flow as the Mach number is associated to the frequency considered. This means that to study the frequency will allow us to make conclusion on the Mach number, as they are here "equivalents" (one is constant when the other is, etc).

To finish, to have quantified the factor α is a good step in our analysis, but as we took a specific example to then generalised to other cases, the conclusion is more about the fact that the dependence depends on the points considered rather than the points where it appears and the intensity calculated. Thereby, we can here conclude on the fact that there is between two and three ranges of points for which the slopes is changing, and that it will mainly happens at the leading and trailing edge. We also consider the order of the frequency's dependence (from 10e-3 to 10e-2) as being reliable enough for the following comparison.

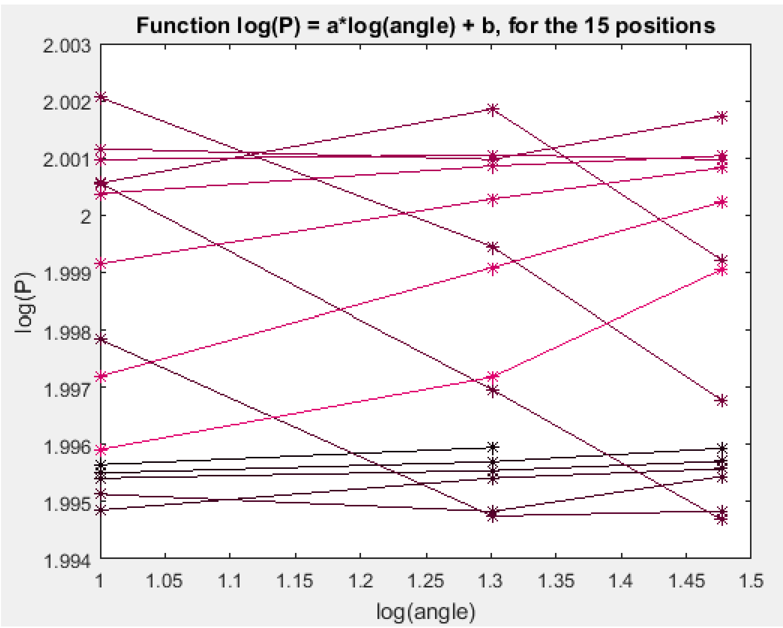
Furthermore, we are also willing to put the factor α in comparison with β and then see the dependence on the angle. Indeed, this is not the values that will give our final opinion but rather the comparison that will put in evidence which one of the two variable has the most of influence, and then complement these results with subsidiaries values.

2.1 Influence of the angle

To quantify the influence of the angle over the loading, we are once again gonna use the PI theorem. This theorem is indeed made into two parts : the first one was to determine the influence of the frequency (= the coeff α), and the second where we do the same method but for the angles.
Thereby, we have to determine the coeff in the equation that follows :

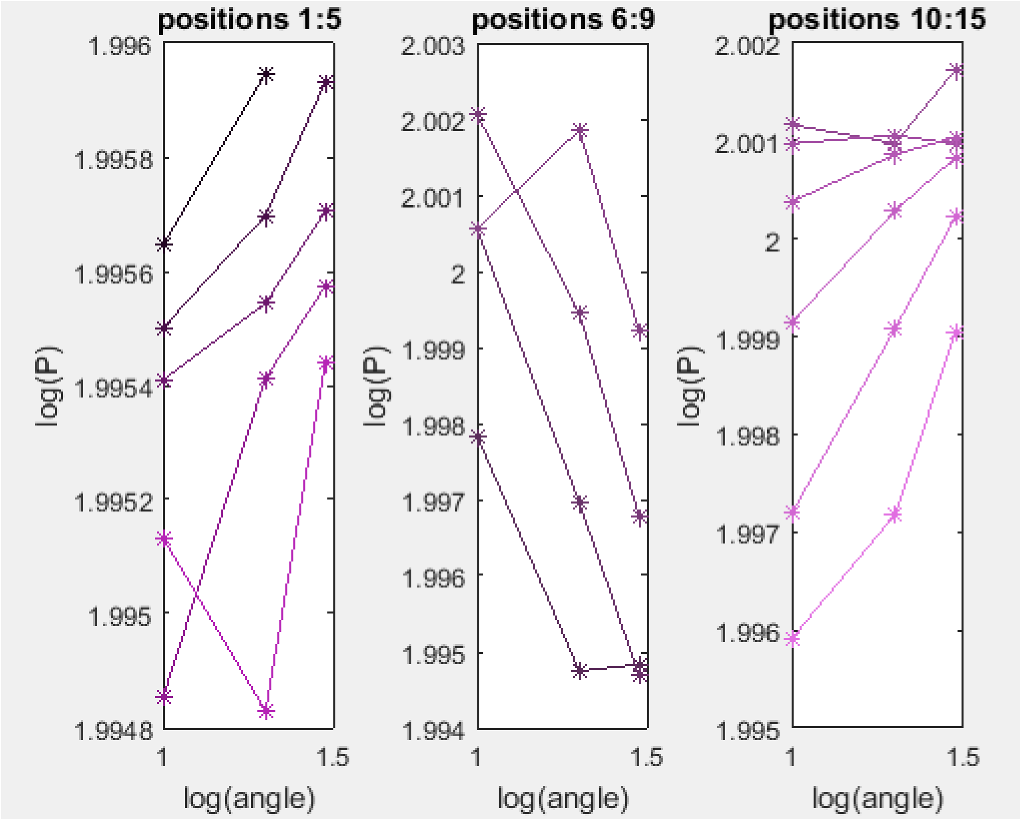
$$Aero\ \ loading = Cst * Angle^{\beta} \tag{4}$$

In order to do so, we will consider the cases where the frequency is constant and then see how the loading varies with the angle. Once again, to shorten the report, we will take a look to the blade b0, at a defined frequency (freq = 15), letting the other graphs for the reader's curiosity thanks to the Matlab code.
In this first diagram, we decided to show for every 15 positions of the sensors, the influence of the angle. To do so, we have plotted the log of the loading in function of the log of the angle, the other potential variables staying constant, they appear once again within the constant :



As we can see, the results show lines as expected, but they don't all have the same slope. This means that the influence of the angle also depends on the points considered. We will then plot the same curves but by splitting the graphs for some ranges of point.

Thereby, we have bellow a clearer splitting showing different degree of influence depending on the considered point :



On those new figures, even if some slope can differ a bit, we here too can see that the dependence is also a matter of considered sensor (and associated point on the blade). We have informations close to the one we had for the frequency :

— a variation in the dependency ;

— transitions in the dependence that appear close to the seventh value, so at the leading edge, and at the trailing edge.

As we are considering other frequencies, it might implies that our previous assumptions were relevant enough to be extrapolated for the other cases. Nevertheless, as e are still considering the blade b0, we won't do any more sharp conclusion on these observations.

In the table below we gathered the numerical information of the slopes for a frequency of 15 and an angle form 10 to 20 through 15 :

Frequencies / Sensors' position	1 :5	6 :9	10 :15
15	3.971*10e-4 **3.971*10e-4**	-0.0045 **-4.5*10e-3**	0.0016 **1.6*10e-3**

To conclude with this part, we here have three ranges for the points (even if the ranges 1 : 5 10 : 15 are kinda from one big range) and we here too have a transition in the dependence from proportional to inversely proportional.

2.2 Conclusion

We have only little dependence either over the angle or the frequency but at their scale, we still got data confirming what we assumed before. Indeed, we can see that the dependence over the angle is from 10e-4 to 10e-3 while it was approximately ten times greater for the dependence in frequency.

The final point that we are willing to put forward is that we have both numerically and visually made remarks and observations that are inter corroborated and that lead to confirm our first assumptions/observations.

Gathering the numeric data we have for α and β, we have the following equality :

$$Aero\ loading = Cst * Frequency^{\pm 10e-2} * Angle^{\pm 10e-3} \tag{5}$$

We also see more clearly the global dependence on each point and have a better hindsight on the scales of dependence that go with aerodynamic loading.

3 Unsteady Loading

In this part we will take a deeper look to the loading by looking to the unsteady part, for instance implied by the flutter phase. We thus complete the precedent section by looking to this case of unsteadiness.

We will be working with values that include unsteadiness, and so losses, and we will then have to "fix" the pressure values thanks to a Matlab code. This part won't be further explained as she is already detailed in the lab notes.

The scheme of this part of the loading's analysis is made as follows :

— We ran the experiment gathering data for unsteady loading ;

— We take into account the losses using a Matlab code ;

— We study the blade b0 to then extrapolate for the behavior of the other blades ;

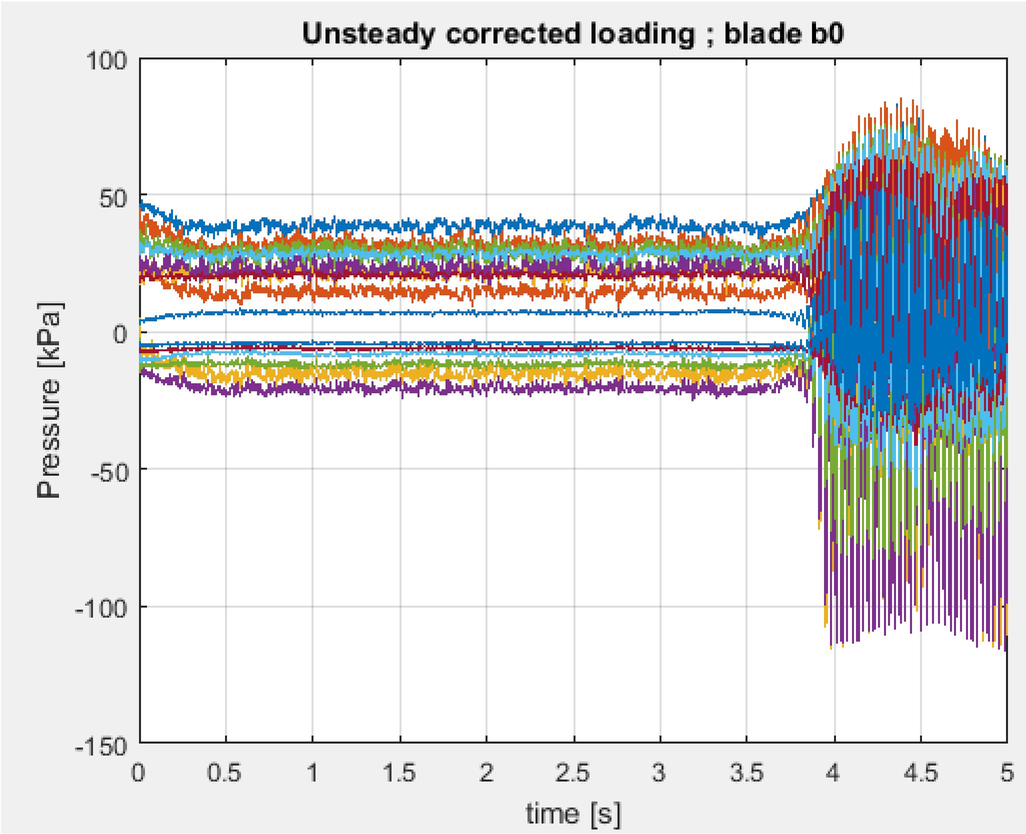
— We conclude on the informations gathered by the post-processing : error bands for each 15 taps.

We specify that the analysis of the unsteady flow as been run for an angle of $\alpha = 10°$ and a frequency of 32 with a spring length of 53.

Thereby, to compare steady and unsteady flow we will be considering this unsteady data and the steady loading for the same configuration. Even though we are only considering the data for one frequency and one angle, the point here is that we consider the pressure along time, and thus we have a several data with respect to this variable.

3.1 Unsteady loading - corrected

In the diagram below we display the curves for the unsteady loading, which can been seen as variations for the steady loading. This means that the loading will be given within a range of existence itself given by the unsteady loadings :



We clearly see on this graph that :

— the unsteadiness is also depending on the considered point of the blade

— the flutter part appears at t = 4s

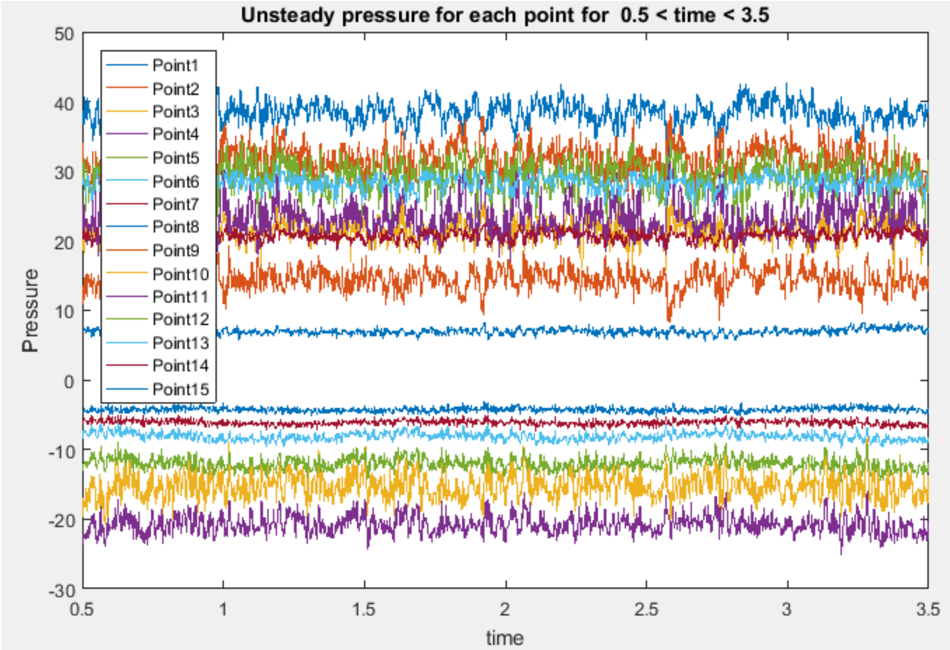
These two informations are leading us to study the loading with respect to each point and to do so we are first gonna show an exemple on a specific point. To do so, we decided to consider the point 1 of the blade 0 and we used this example to all in all have more hindsight on the unsteady pressure.

We then did as follows :

— We adapted the range of variation to the associated steady pressure : we calculated the necessary coefficient to have a pressure at ± unsteady pressure ;

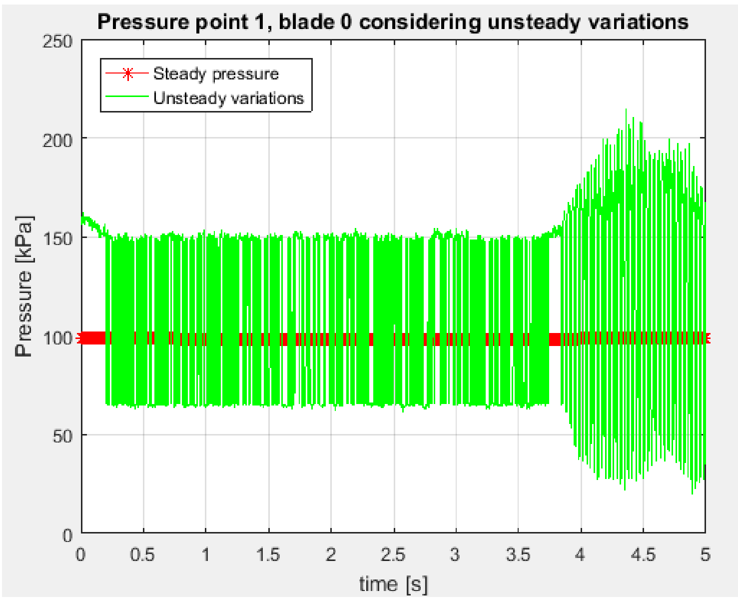
— We shifted the pressure so it fits to the steady pressure.

First, we got an idea of the unsteady behavior before the flutter thanks to this graph that we plotted :



We then used the information in this range of time to work on the loading's maximum pressure points, the frequency of the signal, etc. In fact, we used this specific observation at a certain range of time for the point 1 of the blade b0 to then build the necessary functions and methods you can have access to through the Matlab code.

It led us to our second point : extrapolate our researches to the entire range of time. Therefore, on a second time, we made the following graph where we represented the result of the points listed above. By plotting the steady pressure of the point 1 as well as the associated unsteadiness (range of fluctuation) we got these results :

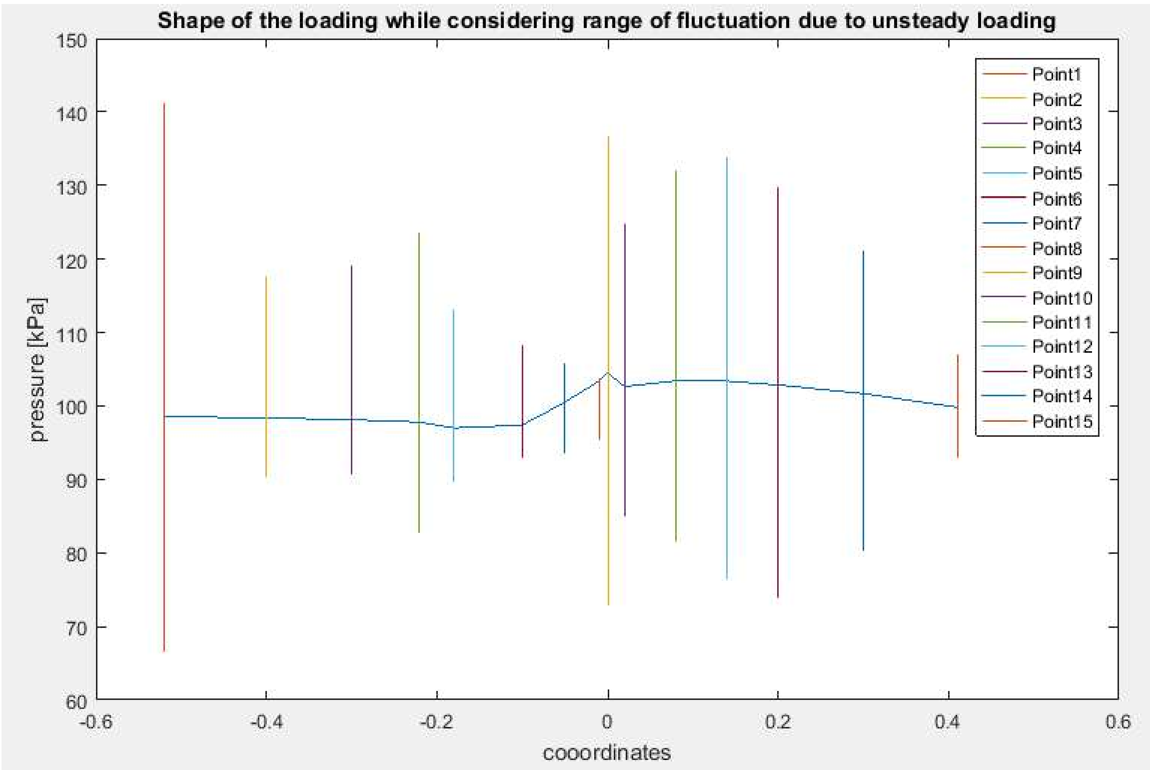


Our final objective back to this time was to then expands the study on a specific point to each of the 15 taps for one blade. Nevertheless, before doing this, we took the decision to take a look to the unsteady data gathered at this point to see what they told us.

On one hand, we clearly see here that, even more than with the steady data, each point of the blade brings its amount of turbulence and losses. The one that present the less unsteadiness are the points around 15 and 8, at the trailing and leading edges. Contrary to what we could have been made to think, the trailing edge, at least for the considered case, isn't presenting the biggest unsteadiness, on the contrary.

One the other hand, even if those plot are giving us useful informations, under this shape, they are quite difficult to apprehend and they are hardly comprehensible.

In order to make informations much clearer, we used the previous informations gathered to make a final plot, the one showing the overall loading of the blade b0 and implementing the error bands we were aiming to get :



We have finally a clearer sight of the unsteadiness of the loading depending on the points on the blade. We then see that the unsteadiness is the lowest on the SS until the leading edge where begin an increasing in the unsteadiness until the trailing edge where it is diminishing. Globally speaking, we have here a visual information of the observations we did before regarding the point at which the transitions were appearing for example.

We can see that the ranges of fluctuation are of the same order than the steady value and thus that the losses make it difficult to have precise and finite information on the loading. We can although confirm some of our assumptions and make some new, to see below.

3.2 Conclusion - Unsteadiness

As a conclusion, we saw that the unsteady loading appears physically as a range of existence for the steady loading and we argued this with mostly visual informations.

It allowed us to see for instance that, as the dependence is changing of mode at the trailing and leading edge, these area are the one where the losses are the lowest as there is approximately zero dependence on either the angle or the frequency there : the shifting operating in these areas tends to explain the losses being low at the same area. It is kind of a bump at those point that make diminishing the influence in these area and that looks to have an influence on the overall loading.

If we consider only the unsteady loading, we see that even from data from the flutter part, we have a clear detail of the range of fluctuation for the pressures.

Even though those observations make sense, we recall that our observations are to put in contrast with the study framework : we made big assumption on the fact that a blade was possibly extrapolable for the rest of the raw of blade. We also work with very low valued that may have been influenced by either the lab experience we did or the post-process methods.

4 Conclusion

To finish with this experiment, it allowed us to get a better hindsight to how behaves the loading in a steady case, in an unsteady case, to see the physical elements acting on the loading (spring length, frequency, etc) ; and we were able to make relevant observations bonding our visual observations to numerical informations for both steady and unsteady loading.

The dependencies from the frequency and the angle have been compared and they finally gave us a set of informations that tend to be corroborated by the unsteady loading study. We also made quantification arguing and confirming the reliability of the methods used (PI theorem, extrapolation, etc) as well as underlining the pertinence and the precision of the experiment itself.