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Construction of a new fast-opening device for dynamic calibration of pressure transducers

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Abstract. *Developments in the studies of transient processes created the need for precise measurements in non-stationary situations. These measurements require the calibration of sensors in respect to their dynamic behavior. But reference standards that can be used as the base for this calibration are not readily available. In dynamic sensor calibration, the relationship between the output signal generated by the sensor and a known input signal, both variable in time, must be determined so that the dynamic characteristics of the sensor may be obtained.*

The dynamic behavior of a pressure sensor can be modeled by a differential equation, but its determination for a real sensor is not trivial. To solve this problem, often the sensor is characterized from experiments that determine its Transfer Function. With the objective of covering the multiple types of pressure sensors available, and their multiple pressure and frequency ranges of operation, different types of calibration devices have been developed, including the Fast-Opening Device. One such device has been in use at the Laboratório de Metrologia Dinâmica at UnB.

The main purpose of this work is to design a new low-pressure chamber for the Fast-Opening Device, with an alteration to the way that the sensor is attached, allowing the exploration of advantages in the use of automatic pressure control. The new design is supposed to extend the working frequency range of the device, with a 1% uncertainty, from 50 to 300 Hz.

Keywords: *Calibration, Fast-Opening Device, Pressure Sensor.*

1. INTRODUCTION

Measurement of pressure, in general, is done in static conditions or in situations where pressure variation occurs at very slow rates. This is the case in many industrial processes, where static measurement of pressure is all that is needed. Even in cases where the rate of pressure variation is low, the measurement can be considered as “static” (where no doubt exists in respect to the ability of the sensor to follow the pressure time history).

With the advent of new industrial processes and research in transient processes, the measurement of pressure in non-static situations became necessary. Not only the steady state value of a given measurand (if it exists), but also the evolution of the measurand in time is required, as result of a measurement. Thus, in these cases, the sensor used must be able to produce an output signal that reproduces, with known uncertainty, the behavior of the measurand. In these cases, the measurement is called of dynamic measurement of pressure, and is becoming very important in applications in aviation and aerospace technology (ISA-37.16.01-2002, 2002) and other applications, such as automotive, for example.

Dynamic measurement of pressure demands the use of fast time response sensors. In general, sensors based on piezoelectric materials best approach this requirement, presenting relatively high natural frequency for the sensing element (Hjelmgren, 2002). However the dynamic behavior of whole the sensor (including pressure lines, if used) must be known. For the reliable operation of a pressure sensor in dynamic conditions, with known uncertainty levels, a dynamic calibration procedure is necessary.

However, primary standards for dynamic calibration of pressure sensors do not exist. Differently from static metrological standards, or even steady state standards for time varying quantities, convenient physical metrological standards cannot be specified. This heightens the difficulty of prescribing a calibration procedure in these cases. The lack of practical physical standards, such as those available for static calibration of pressure sensors, for example, results in the specification of dynamic calibration procedures that rely on a reference sensor for the calibration procedure.

The sensitivity is not the most important characteristic to be obtained in the dynamic calibration procedure of pressure sensors. The main objective of the dynamic calibration is to obtain the Transfer Function for the sensor, relating the sensor output signal to the pressure signal being measured as gain and phase information, in the frequency domain (Damion, 1994). While other parameters (like ‘rise time’, ‘response time’, etc.) can be used to illustrate dynamic behavior, only the Transfer Function really characterizes it.

Dynamic calibration procedures for pressure sensors are based, as a rule, on comparison with a reference sensor. But it is certainly required that the reference sensors themselves have been calibrated within strict metrological practices. For this, various types of metrological dynamic pressure generators have been developed (Diniz *et al*, 2003). Each of them operates in a given frequency and pressure range. Utilization of several of these devices allows for an extended frequency (and/or pressure) range.

1.1. Objectives of this work

A Fast Opening Device is currently in use at the Laboratório de Metrologia Dinâmica of the Universidade de Brasilia (Neves and Fritsche, 2002). It is the objective of the work here reported that a new Fast Opening Device is designed and built. Improvement of the performance of the existing apparatus is sought, so that a primary calibration device be made available with specifications allowing for calibration in the 0,1 Hz - 100 Hz range with maximum of uncertainty of 1%. Inter-comparison tests for this research will be carried through a partnership with ENSAM in France and the participation of INMETRO in Brazil.

2. THE DYNAMIC CALIBRATION OF PRESSURE SENSORS

Diverse types of existing pressure sensors in the market demand different ways of dynamic calibration (Diniz *et al*, 2006), depending on the type of sensible element employed.

For the dynamic calibration of pressure sensors dynamic pressure generating devices are necessary. The principle in which these devices are based can separate their method of operation in two basic groups:

- Periodic methods
- Non-periodic methods

Both methods of calibration seek to determine Transfer Function of a device being calibrated. In the first one a periodic pressure signal is generated (in some cases attempting to obtain frequency response data directly), while in the second case a non-periodic signal is generated (in most cases a step approximation) from which the frequency response data must be obtained. In both cases a device that generates a pressure signal that will be used as reference in the calibration procedure must be used. Obviously the *quality* of the generated signal, with respect to the theoretical function the device attempts to physically reproduce is of the utmost importance. Clearly, in the impossibility of producing a perfect physical pressure signal (with no deviation from the mathematical time function it attempts to reproduce), it is necessary to evaluate the deviation of the signal generated by the device with respect to the theoretical function aimed at. For this the calibrating device must, itself, have its frequency response well determined (using the theoretical function as reference). One can then (taking into consideration the frequency response characteristics of the device, and frequency response obtained for a given sensor output signal with respect the pressure signal generated) indirectly infer, within given incertitude, the frequency response of the sensor. If a reference sensor is used, the dynamic calibration is obtained using the calibrating sensor signal as output and the signal form the reference sensor as input in the frequency response algorithm. But still the problem of calibration of the reference sensor persists.

2.1. Non-periodic pressure generators

These devices are designed to generate well defined non-periodic pressure signals. In general step function is sought. The “closed bomb” would be the most obvious, but also one of the least reliable, forms of such a device. In this device pressure steps are generated through the explosion of a small explosive load in the interior of a closed chamber, where the sensor to be calibrated is mounted. The detonation the explosive creates a pressure step of infinite duration (except in devices where a special system allows the relief of pressure after a specified time interval). But low repeatability requires the use of a reference sensor in the calibration procedure. Undesirable features of this device include difficulties with the control of the final pressure of the step generated, and a high dependence of the signals obtained on the position of the sensors in the chamber, both for reference sensor and the sensor being calibrated, which increases the uncertainty related to the possibility of having each sensor sensing different pressure time histories.

Two other non-periodic pressure-generating devices, which can generate controlled metrological time pressure functions, are the shock tube and the Fast Opening Device. In general these devices operate in different usable frequency ranges, so that the use of both in the calibration of a single sensor has been recommended, in order to extend the global frequency range of the calibration (Oliveira ,2003). A brief description is given bellow.

2.1.1. The shock tube

Widely used for dynamic calibration in the higher frequency range, the device consists of two sections of pipe separated by a thin diaphragm. These two sections are initially pressurized at different levels. When the diaphragm is suddenly punctured, a shock wave front travels in the fluid from the high-pressure section to the region of low pressure. The passage of the shock wave produces a short duration pressure step, which is used in the dynamic calibration. The processes occurring in the shock tube are well documented in the literature (Barcelos et al, 2001). Hence the shock tube qualifies as step pressure generator for metrological application. The generated step is, in general, fast (has small rise time), resulting in a signal that can be used in calibration in comparatively high frequencies, in a range extending form 100 Hz to 10KHz and a possible pressure range varying from 0.2 to 2.5 MPa (Diniz *et al*, 2003). The pressure signal generated depends on the control of certain parameters. These include the diameter and the length of each section; the material of diaphragm; the method for puncturing it; the stiffness of the tube; the roughness of the wall; the temperature and pressure of the fluid used.

2.1.2. Fast opening device

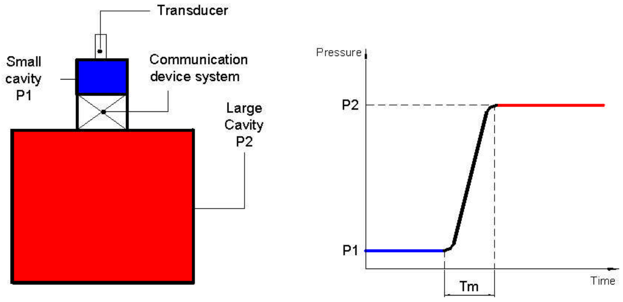

Figure 1. Schematical fast opening device

As the name suggests, in this device, the pressure step is generated throughout a fast opening valve, which allows that the gas from a large chamber at high pressure to occupy a much smaller chamber. The ratio of the volumes of the chambers must be higher the 1000. The sensor to be calibrated is mounted in the smaller chamber, as is the reference sensor, being subject to an initial pressure P1. Pressure in the large chamber is P2, usually higher. When the fast valve is opened, pressure is equalized in both chambers. The principle of operation of the device is that the large difference between the volumes of the two chambers and the high speed of the valve result in an almost perfect pressure step, with a very long duration (practically infinite length), generated in the small chamber. Obviously, the construction of a practical fast opening device poses design problems that must be solved in order to obtain a signal that is as close as possible to the theoretical step that is sought. These design problems are the object of the work being done here. The band of frequencies covered is ample. It covers a region of lower frequencies the than the shock tube, overlapping the lower range of this device. With regard to the amplitude of the generated pressure step, there are no significant limitations, as long as an adequate control of pressure equipment is used.

This type of pressure generator is in general easy to operate and have a good repeatability. They can be used in wide bands of amplitude, typically arriving to 10 MPa.

3. THE FAST-OPENING DEVICE BEING DEVELOPED

The new device is being designed to improve the dynamic response of the old one in operation at the Laboratório de Metrologia Dinâmica at UnB. The high volume ratio between the two chambers and the very high opening speed of the main valve are the two fundamental design requirements. The volume ratio chosen for the device is about 3000. The mentioned requirements, together with the small size imposed for the small chamber by the volume ratio and stiffness considerations (related to the prevention of resonant frequencies in the working range of the device) impose design restrictions that must be addressed.

This equipment is designed to generate positive pressure steps. That is, pressure in the larger chamber is higher than that the smaller chamber; thus on opening of the valve the small chamber experiences a pressure increase. Due to the large difference of volume between the two chambers, the final pressure in the small chamber will be virtually identical to the initial pressure in the large one, thus generating the pressure step, corresponding of pressure difference between the two chambers.

For the operation of the valve, a pneumatic drive is used as a rule, used. It has been established that the “quality” of the step generated is influenced by the pressure applied to the pneumatic drive (Fritsche, 1999).

The device already in operation in the Laboratory presents good repeatability and accuracy in the pressure levels generated. It presents a pressure rise time (defined as the time interval between the moments when 10% and 90% of the final pressure is reached) in the order of 2 ms. Previous studies (Neves and Fritsche, 2002) have shown that, even with considerable high values (reaching more than 0.5 MPa) for the pressure used in pneumatic drive, the rise time can not be significantly reduced. Moreover, the same of work indicates that, as the drive pressure of the pneumatic drive is increased, the overshoot in the real step generated by the device (see Figure 1) tends to increase too, a feature that is undesirable.

The same work has also shown that, the use of gases of small molecular mass, like helium, as the working fluid for the device, improves the rise time. But, even using light gases, the rise time could not be reduced to less than 1.5 ms.

A typical time history graph for the Fast Opening Device in operation in the Laboratory is presented in Fig. 2. In the case depicted the rise time was approximately 3 ms.

The design of a new device with a typical rise time inferior to 1 ms is the object of the work being done, of which part is here presented.

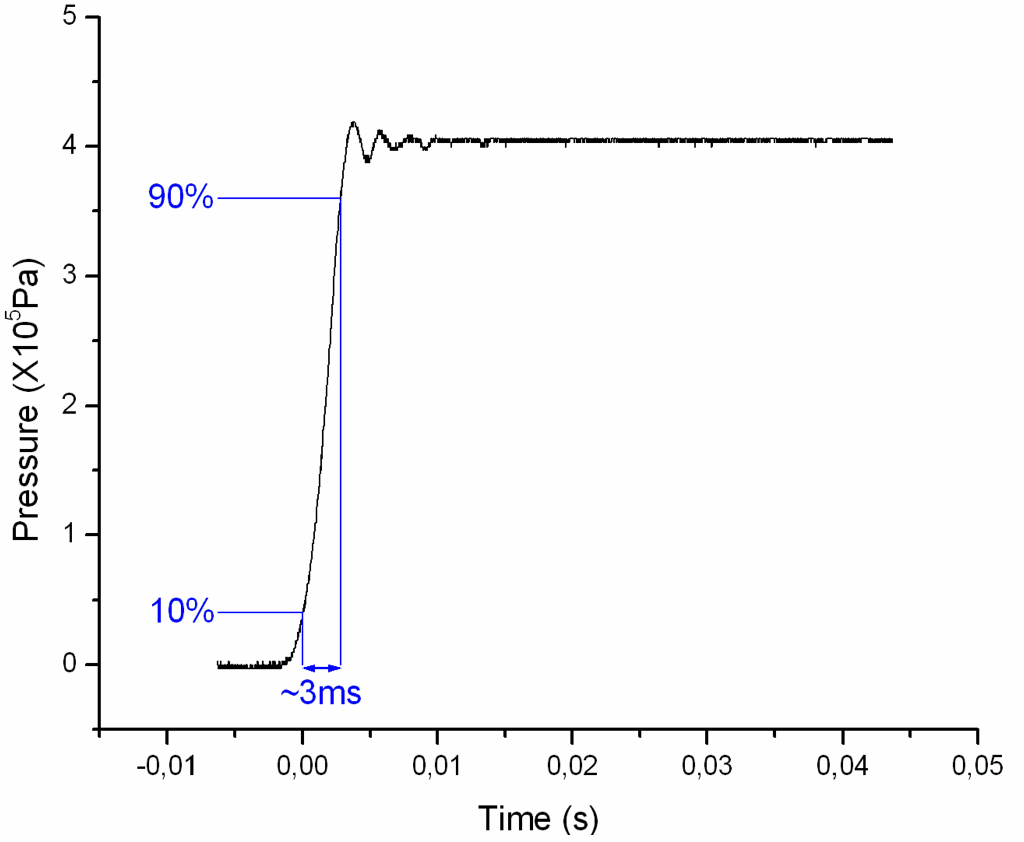

Figure 2. Typical result of test with the existing fast opening device

3.1. Development of the new device

The generator being developed has design specifications that should allow it to be used in a frequency range up to 300 Hz. This will overlap the frequency range of the shock tube, thus allowing for complementary use of both devices, when dynamic calibration of given sensor over an extended frequency range is sought. To obtain this, a rise time of less 1 ms is should be an indication of a fast enough operation, which together with no significant overshoot and/or oscillation in the signal, should result in appropriate frequency response characteristics for the device.

In order to obtain a rapid transit of the fast opening valve, the release mechanism is conceived in such way that the pneumatic actuator that drives the assembly does not impart motion to the valve directly. Instead fast opening is obtained by use of kinetic energy and the impact of a sub-assembly driven by the actuator. It should be noted that a pneumatic powered drive has the advantage of not producing electrical noise that could interfere with the electrical signals generated by the sensors in the calibration process.

For the large chamber a 53 liter cylindrical pressure vase with spherical extremities is used. The dimensions are such that the lowest natural frequency of a sound standing wave in interior of the cylinder is above 300Hz. Hence it does not interfere with the dynamic calibration process. The vase is certified to withstand an internal pressure of 2 MPa. Figure 3 shows the main parts of the device with their location in the device in a isometric view.

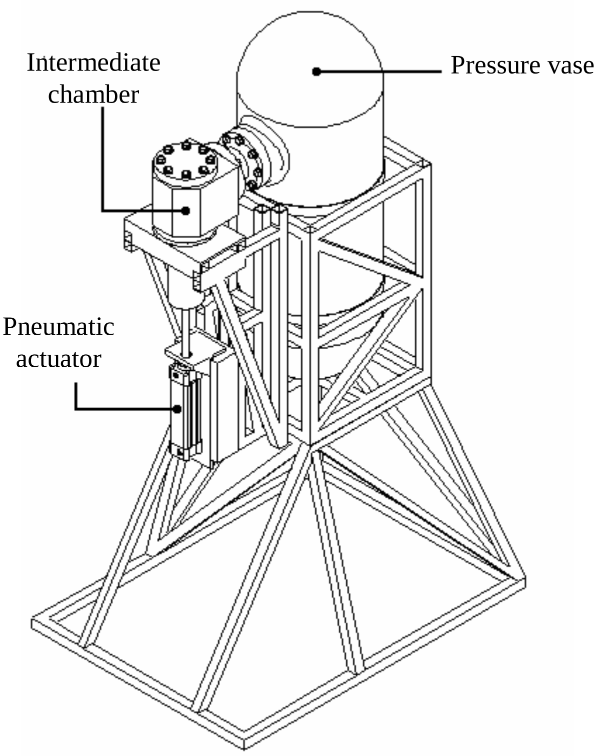

Figure 3 – Illustrative isometric view of the device

The large chamber is connected to the fast opening valve, and to the small chamber, through an intermediate chamber. Its diameter of this chamber is much larger than the dimensions of the valve entrance, so that pressure loss it will eventually generate is very low, not impairing in any significant way the design target of a very low rise time. The intermediate chamber has, therefore, three ports, being one of them for the connection to the large chamber through a connecting tube. Fastening of the two is done using a bolted flange.

For the two other holes two different covers are used. One is used to support the opening drive assembly. The other holds the small chamber, with the ports for pressure sensors and the fast opening valve itself. These covers are basically cylindrical plates, held to the flanges of the intermediate chamber by bolts. The assembly is designed to match the proof pressure of the large chamber (2 MPa).

3.2. Structural behavior of the intermidiate assembly

The various parts of the intermediate chamber, as described above, have been modeled using finite elements to evaluate the stiffness of the assembly and its natural frequencies. This is important, since the stiffness of the assembly much contributes to the “quality” of the pressure step that will be generated. On the other hand, resonance frequencies in the work frequency band of the device must certainly be avoided. The simulations were done using the CosmosWorks program, from SolidWorks Corporation. For the stress / deformation simulations the load applied corresponds to an internal pressure of 10 MPa, and the clamping forces between the parts was simulated by modeling the forces resulting form the joining bolts. Some of the results obtained are presented bellow.

3.2.1 Front cover

The simulation for the front cover registered a maximum equivalent Von Mises stress of $1.44 \cdot 10^{8}$ N/m^{2} (localized near a bolt hole), and a maximum deformation registered of $1.057 \cdot 10^{-5}$m (near the centre). The mesh used, the stress distribution obtained and the distribution of deformation over the piece are presented in Fig. 4 and Fig. 5.

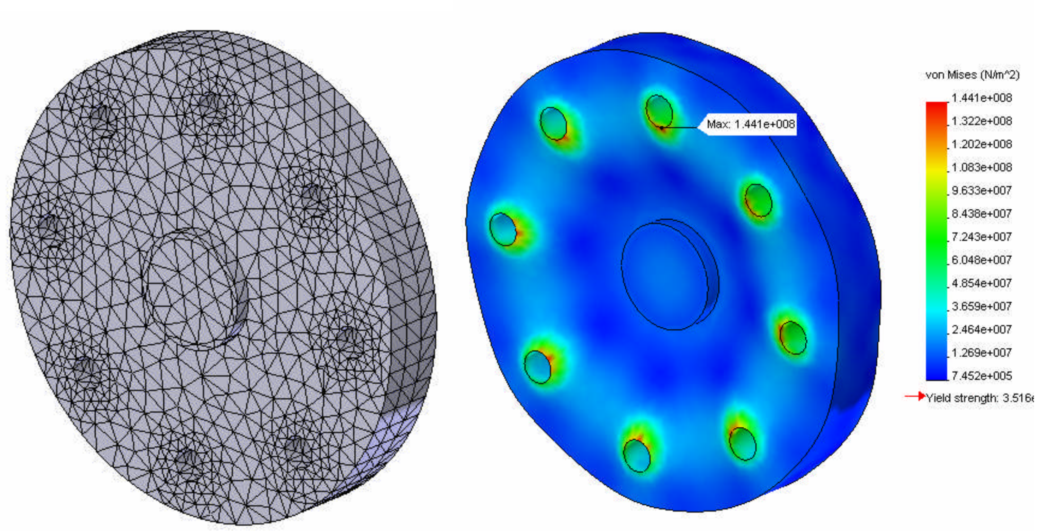

Figure 4 - Mesh used and Von Mises stress for the front cover

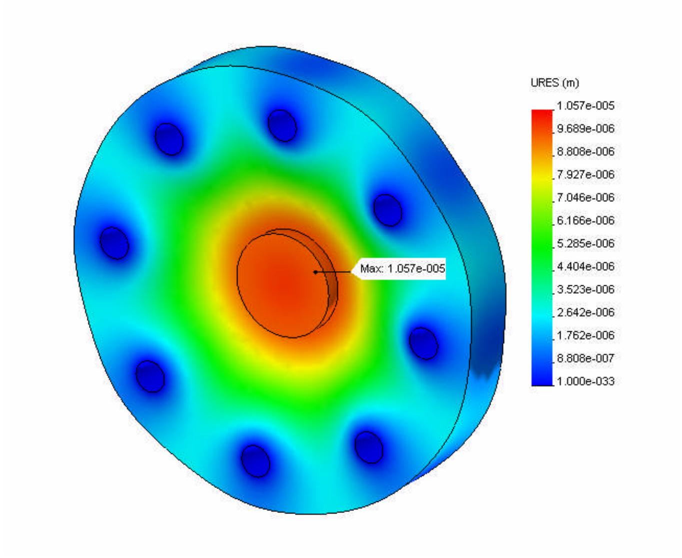

Figure 5 – Deformation distribution of the front cover

3.2.2. Back cover

For the back cover, using simulation method similar that described above, a maximum equivalent Von Mises stress $1.64\cdot10^8$ N/m^2 was calculated. Again this is a localized stress near a bolt hole. The maximum deformation obtained was $1.633\cdot10^{-5}$m.The mesh, the stress distribution and the deformation are shown in Fig. 6 and Fig. 7.

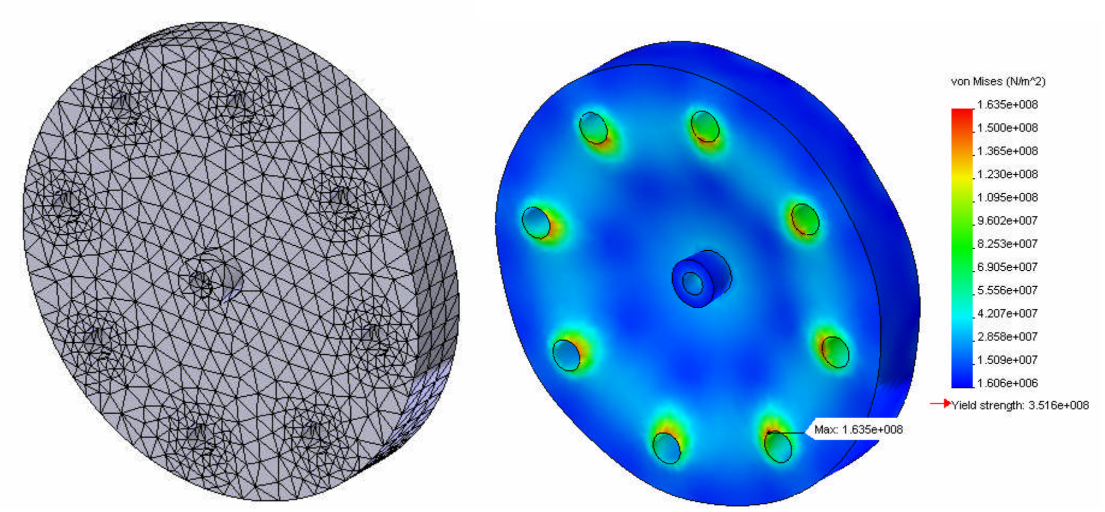

Figure 6 - Mesh used and Von Mises stress for he back cover

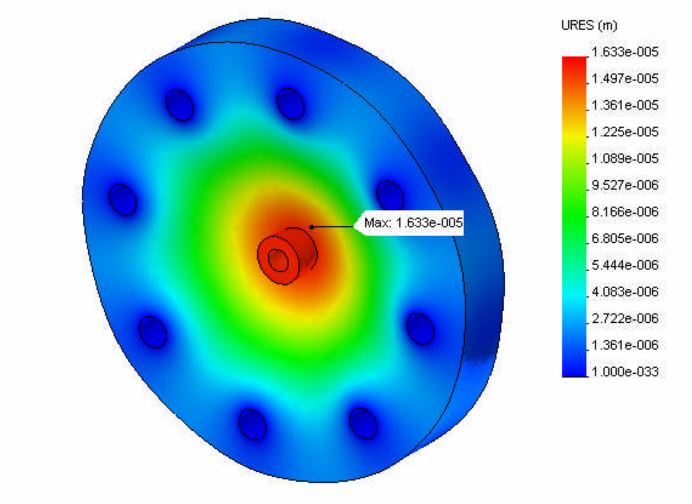

Figure 7 – Deformation distribution of the back cover

3.2.3. Intermediate chamber

Once more the intermediate chamber was modeled assuming the specified internal pressure and the forces applied by the bolts. The maximum Von Mises stress of $2.46 \cdot 10^8$ N/m^2 was obtained, and the maximum deformation observed was $8.56 \cdot 10^{-5}$m. Figure 8 shows the mesh and the stress distribution for this part, and Fig. 9 shows the deformation distribution observed.

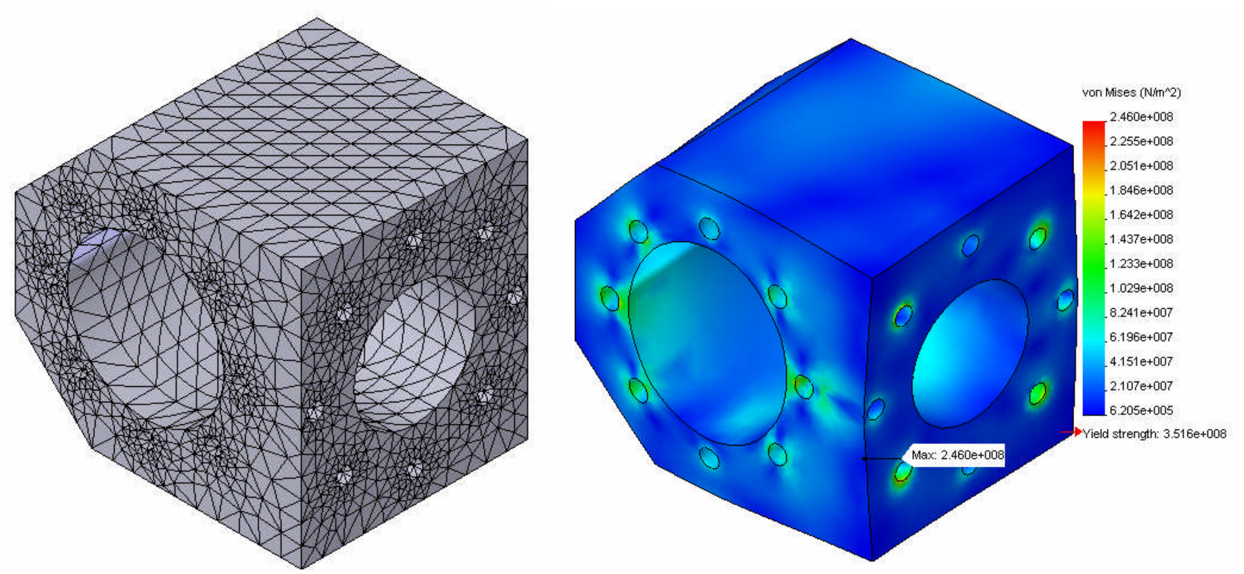

Figure 8 - Mesh used and Von Mises stress for the intermediate chamber

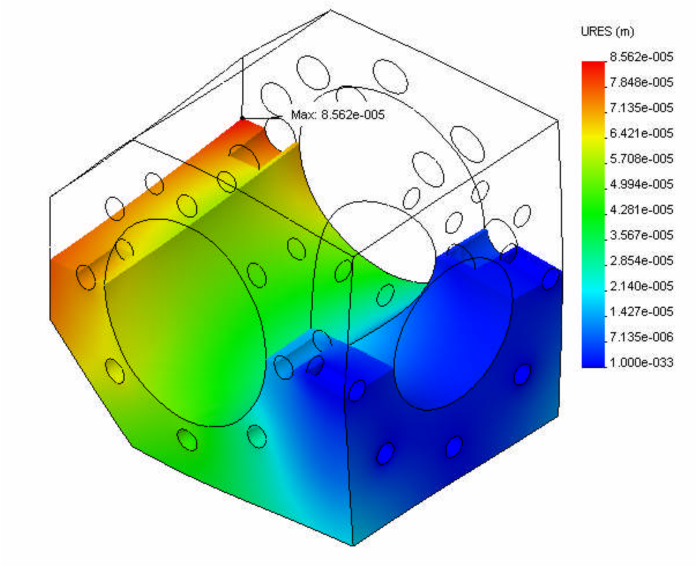

Figure 9 – Deformation distribution of the intermediate chamber

3.2.4. Connecting tube

The loading for the simulation of this component was, again, the internal pressure of 10 Mpa, as well as the loads resulting from it on the bolts. Maximum Von Mises stress of $2.2 \cdot 10^{8}$ N/m^{2} and a maximum deformation of $7.71 \cdot 10^{-5}$m were obtained. Figure 10 shows the mesh and the stress distribution for this part, and Fig. 11 shows the distribution o deformation observed.

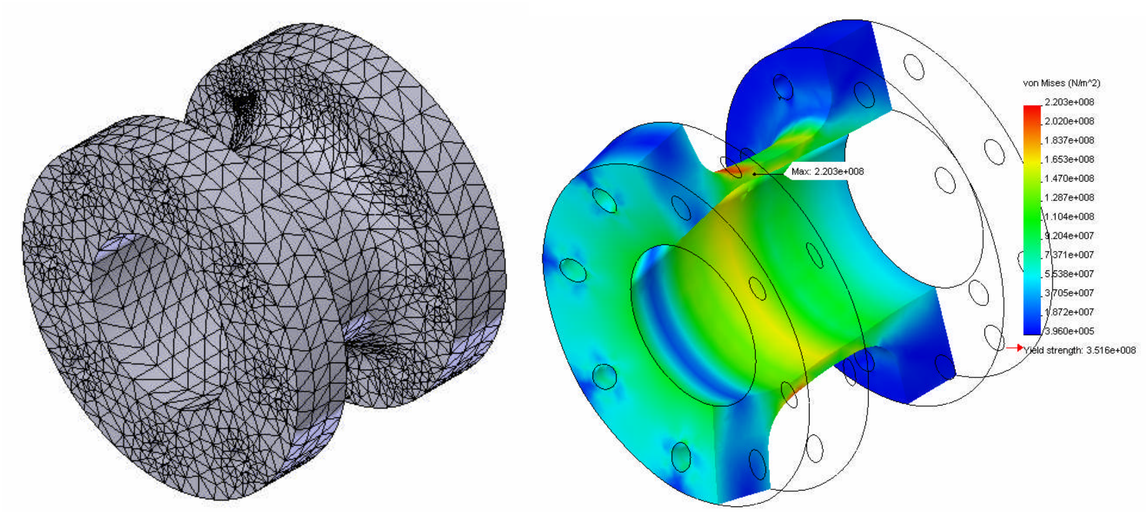

Figure 10 - used mesh and tensions of Von Mises in the connection part

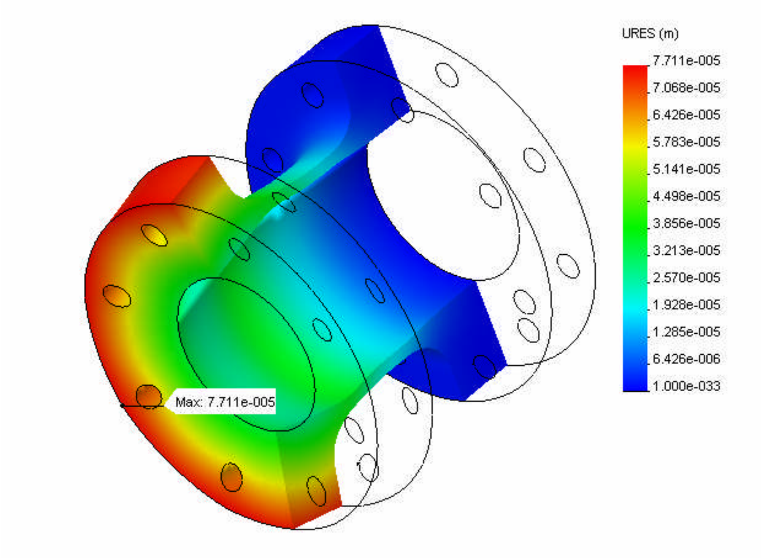

Figure 11 – Deformation distribution of the connecting tube

3.2.4. Natural frequencies

As stated above it is important that both frequencies of standing waves that may occur in the large chamber and resonant frequencies of the structure that makes up the fast opening device stay away from the operating frequency range of the device. Hence the 5 first natural frequencies for the intermediate assembly were calculated using the finite element software. The values obtained are presented bellow in Table 1. It can be seen that these frequencies stay well away from the 0 to 300 Hz band.

Table1 - **N**atural frequencies for the intermediate assembly, obtained by finite element simulation

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)
1	17883	2845
2	18219	2898.5
3	19036	3028.5
4	33745	5368.6
5	33846	5384.6

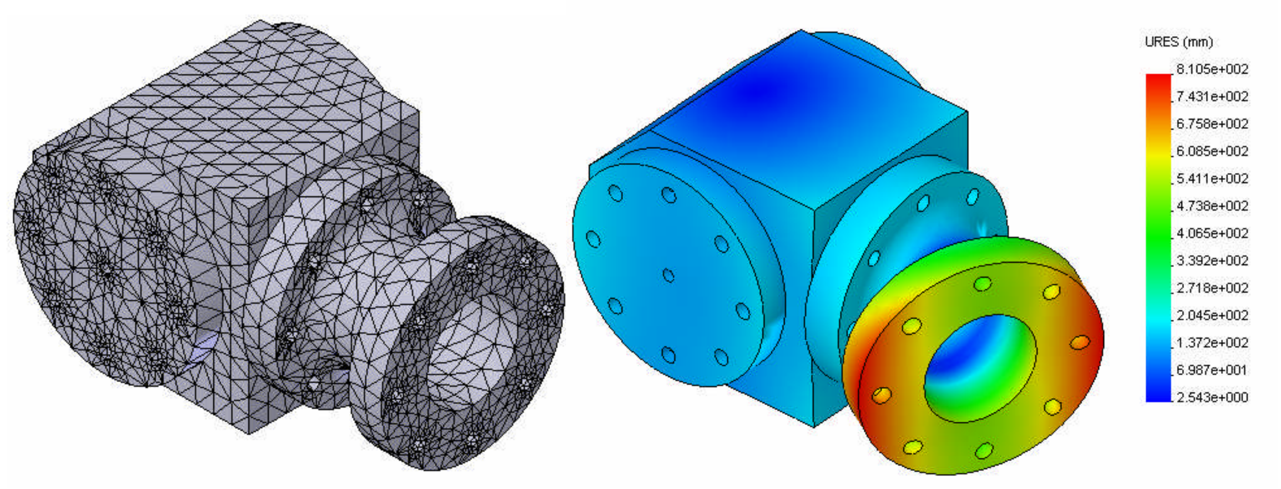

Figure 12 - illustrates the configuration of the mesh used and the first mode shape.

4. CONCLUSION

A new design for the fast opening device was proposed with the goal of considerably lowering the time necessary to fill the small chamber, thus reducing the rise time of the pressure signal generated. All the while, this should be achieved with a *clean* signal, with as little overshoot and/or oscillation as possible, approximating as close as feasible a theoretical step, the aim being to obtain a flat frequency response for the device in the range 50 Hz to 300 Hz

Finite element analysis of a new intermediate chamber/connection/support sub-assembly between the large and the small chambers was performed in order to determine the levels of deformation in the various parts under the pressure loads expected for the device. These are important, since high rigidity is sought, so that no parasitic effects will be present during operation of the device. As a byproduct, stress levels were calculated, so that integrity of the assembly is assured.

The finite element simulation made the natural frequencies and mode shapes for the sub-assembly available. These indicate that natural frequencies are high enough to clear the operating band of the device. Thus ressonances generated in the structure will not interfere in the dynamic calibration procedure. The same can be said about standing waves occurring in the large chamber. So, structural dynamic effects should be well decoupled from the dynamic processes occurring during the calibration process, these last ones being the object our design efforts.

The new fast opening device being built should have an extended frequency range, while maintaining the pressure operating range that the existing devices. Experience gained operating and designing some of those devices, both at the Laboratório de Metrologia Dinâmica, UnB, Brasília and at the Laboratoire de Métrologie Dynamique, ENSAM, Paris, indicates that this will be the case.

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