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Modal Analysis of Medium Calibre Barrels

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Abstract. The paper deals with modal analysis of the two different medium calibre barrel weapons. At present time PC software which are based on FEM modal analysis enable not only create a new design but also check old design how be up to standard on the fire accuracy. Also at this time is big boom to make new armour personal carriers which are equipped with the medium weapon calibre systems. Many of them use standard design of bedding the barrel to the weapon case, however also they are created in new weapon design. The modal analysis is powerful method to describe their vibration properties which have the cardinal influence on the accuracy of fire. The barrels were modelled as 3-D objects with next configuration with aim to obtain right results and their mutual comparison. Figures 1-3 show design of the solved barrels. Modal analysis was performed by LS-DYNA software using iterative Lanczos method.

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In Tables 1-5, the natural frequencies for these barrels and their modifications and their corresponding own shapes are listed. Next Figures 4, 7-10, 12 show the courses natural frequencies versus modes. In Figure 11 are shown the modal shapes of the modified cylindrical weapon barrel with the armature.
Keywords: natural frequency, modal shape, weapon barrel, finite element analysis

1. INTRODUCTION

The barrel vibration has influence on the accuracy of firing gun due to the up and down jump during the projectile launch. This mainly therefore, that no weapon barrel is perfectly straight, also the projectile is not symmetrical at its axis and the barrel loading conditions from powder gasses are very dynamical and variable. That means that the barrel vibration during shooting makes the projectile impact on the barrel bore very vague, which is a cause also an initial vibration of the projectile and affect gun's firing accuracy. Some authors deal with this problem of the barrel vibration of the medium calibre weapon barrel [1, 2]. In present-day the 30 mm weapon barrels are very spread at using in armour personal carriers. Some medium weapon barrels are used in the standard designs and some of them have the new configurations as the slots in the outer diameter of the barrel or gripping barrel with the armature near the barrel muzzle and next to the superstructure. It will be good to know a behaviour of these configurations during a shot. In the first approach we can by modal analysis obtains how these configurations are stiffness.

2. NUMERICAL MODAL ANALYSIS

The problem of vibration is very often solved as an eigenproblem. The equation for global finite element system is:

$$\mathbf{KD} + \mathbf{M\ddot{D}} = \mathbf{F} \tag{1}$$

where: K and M are the global stiffness and mass matrix respectively, D is a vector of all displacements at all the nodes entire problem domain, and F is a vector of all the equivalent nodal force vectors. For a structural system with a total DOF of N, the stiffness matrix K and mass matrix M in equation (1) have a dimension of $N \times N$, where N is usually very large for the practical engineering structures [3].

The effective procedures for calculation of only a few eigenvalues and corresponding eigenvectors by finite element equations have been developed with Lanczos transformation based on iterations [4]. In this technique we first have to solve the homogeneous equation (1), where we consider the case F = 0 .

For a solid or structure equation (1) undergoes a free vibration which is described by equation:

$$\mathbf{KD} + \mathbf{M\ddot{D}} = 0 \tag{2}$$

For the solution of the free vibration problem is assumed a harmonic motion and the displacements are described by harmonic function:

$$\mathbf{D} = \phi\exp(i\omega t) \tag{3}$$

where Φ is the amplitude of the nodal displacement, ω is the circular frequency of the free vibration, and t is the time.

Substituting equation (3) to equation (2) we obtain:

$$[\mathbf{K} - \omega^2\mathbf{M}]\boldsymbol{\phi} = 0 \tag{4}$$

where its solving we get the N desired eigenvalues, which relate to the natural frequencies of this system. The natural frequencies are very important characteristic of the structure which is carrying dynamic loading.

To solve the problem which is stated in introduction, the FEA software has been used to create 3-D models of the barrels and their other parts in the LS-DYNA program [5]. The two different configuration barrels were prepared for the modal analysis and also with modification fixing barrel to the weapon case. The first barrel is conical with outer diameter 67.8 mm for the cylindrical part where is the barrel fixing and next goes to the barrel muzzle with outer diameter 50 mm. The second barrel is cylindrical with outer diameter 67.8 mm. The cylindrical barrel was also investigated at fixing from 500 mm to 660 mm with the aim to show influence the fixing on the natural frequencies. Next both types of these barrels for all modifications were investigated at fixing 660 mm with total length of barrel 2 410 mm and with different design of outer diameters, where are made four slots at two modifications under 90° and 45° from axis y with different depth for each ones. Also the both barrels are modified with muzzle brake which its dimensions are: outer diameter 100 mm and length 100 mm. The muzzle brake is the additional weight attached to the muzzle barrel. Also the barrels were gripping near the barrel muzzle by the ring with armature which its end is fixing to the weapon case. All barrel chambers were created for cartridge 30 × 173 mm. The barrels were created with 8-node hexahedral solid elements and each basic model has 88 572 nodes and 72 300 solid elements. The barrel´s material and additional accessories are from steel with parameters: Young´s modulus = 2.1×10^5 MPa, Poisson´s ratio $\mu = 0.3$ and specific mass density $\rho = 7850$ kg·m^{-3}.

In Figure 1 is shown the conical barrel model with a cylindrical part for fixing (left side) and four deeply slots layout 90° from axis y in a conical part of the barrel. Figure 2 shows the cylindrical barrel model with four slots layout 45° from axis y and with a muzzle break, and Figure 3 shows the cylindrical barrel with the armature and muzzle break.

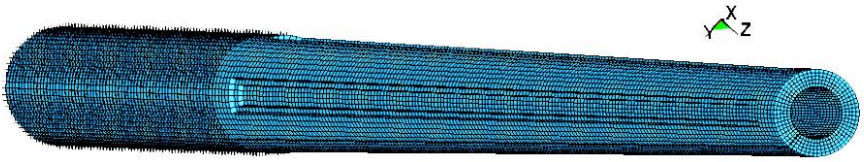

Fig. 1. Conical barrel design with four deeply slots layout 90° from axis y

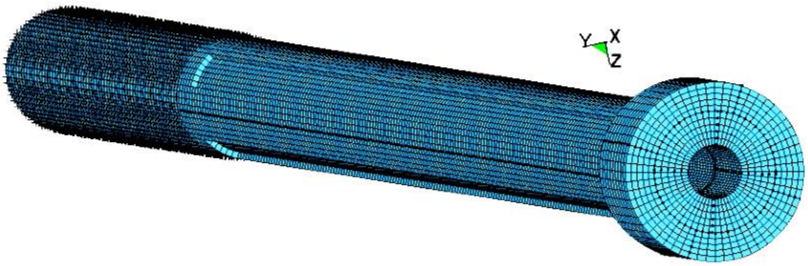

Fig. 2. Cylindrical barrel design with four slots layout 45° from axis y with muzzle break

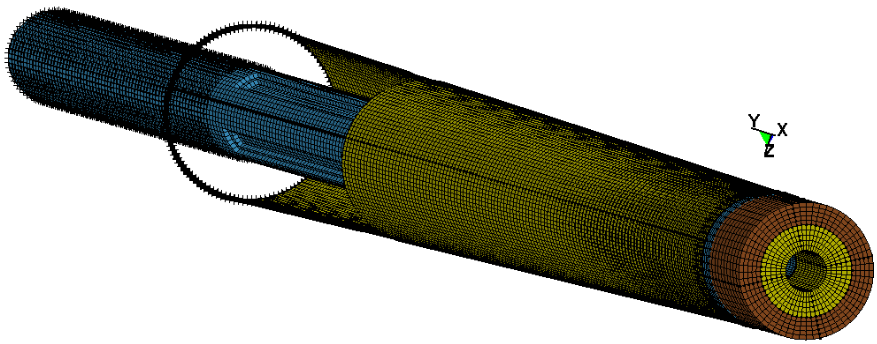

Fig. 3. Partial section of cylindrical barrel design with four slots layout 45° from axis y with fixing, muzzle break and armature

In Tables 1-2 are listed natural frequencies for the simple cylindrical barrel without any slots with modification on fixing with and without the muzzle break. The barrel modification in fixing already is solved for small calibre barrels [6]. Also for medium calibre barrel is important to know, how is the barrel behaviours for its different fixing to the weapon case. This is apparently from Tables 1-2 and Figure 4-5. From these is evident, that when the barrel has longer fixing its natural frequencies are higher, that means, that barrel during shooting will be stiffer. But when the barrel has the muzzle break natural frequencies are smaller than without one.

Table 1. Natural frequencies and corresponding mode shapes cylindrical barrels with different fixing

Mode	**Cylindrical barrel**			
	Fixing [mm]			
	500	**550**	**600**	**660**
1.	14.68/x45°r	15.48/x15°r	16.34/x45°r	17.48/x
2.	91.40/x45°r	96.35/x15°r	101.7/x45°r	108.74/x
3.	253.4/x45°r	266.97/x15°r	281.65/x45°r	300.91/x
4.	418.97 ↕	430.23 ↕	442.11 ↕	457.27 ↕
5.	489.65/x45°r	515.5/x15°r	543.43/x45°r	580.01/x
6.	677.52 ↔	695.75 ↔	714.98 ↔	739.52 ↔
7.	795.44/x45°r	836.71/x15°r	881.24/x45°r	939.44/x
8.	1164.2/x45°r	1223.5/x15°r	1287.3/x45°r	1370.5/x
9.	1256.9↕	1290.7 ↕	1326.3 ↕	1371.8 ↕
10.	1589.2/x45°r	1668.3/x15°r	1753.4/x45°r	1864.2/x

Table 2. Natural frequencies and corresponding mode shapes cylindrical barrels with muzzle break and different fixing

Mode	**Cylindrical barrel with muzzle break**			
	Fixing [mm]			
	500	**550**	**600**	**660**
1.	11.75/x5°r	12.32/x	12.94/x20°r	13.75/x
2.	75.96/x5°r	79.78/x	83.89/x20°r	89.26/x
3.	215.36/x5°r	226.21/x	237.9/x20°r	253.18/x
4.	335.75 ↕	343.04 ↕	350.65 ↕	360.25 ↕
5.	422.73/x5°r	443.87/x	466.64/x20°r	496.31/x
6.	600.66 ↔	614.97 ↔	629.98 ↔	648.99 ↔
7.	694.25/x5°r	728.47/x	765.26/x20°r	813.14/x
8.	1024.1/x5°r	1068.7 ↕	1094.7 ↕	1127.7 ↕
9.	1044 ↕	1073.6/x	1126.8/x20°r	1195.8/x
10.	1406/x5°r	1472.6/x	1543.9/x20°r	1636.4/x

Also when at barrel muzzle is attached a velocity measuring system the natural frequencies fall down and the barrel will be having a bigger yaw. In all tablets in this article the sign ↕ means torsional mode and ↔ translational mode.

Also for e. g. 14.68/x45°r means that first number is the value of the natural frequencies and x45°r is axis x in which the barrel will start vibrate at 45° degree on the right (r).

Again from Tables 1-2 we can see that the direction of the barrel vibrations also changes with the modification of the barrel fixing. That means that the muzzle barrel during shooting will has the tendency vibrate in this direction. The direction of a displacement reveals the missing restraint.

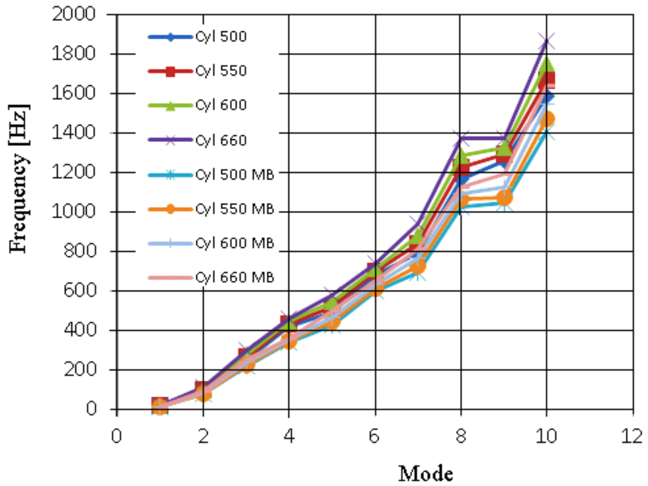

Fig. 4. Natural frequencies vs. modes for cylindrical barrel without and with muzzle break with different fixing

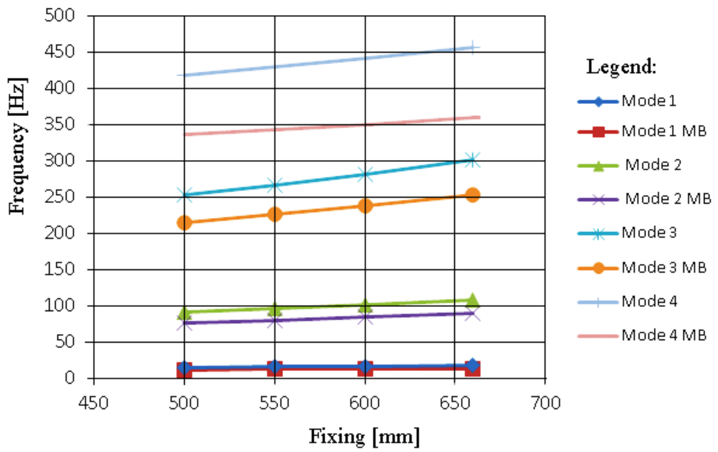

Fig. 5. Natural frequencies vs. barrel fixing for cylindrical barrel without and with muzzle break (MB)

When from the barrel is shoot we can describe barrel´s vibration by three components. The first component is initially (from the fixing) the full cycle, which overshoot a horizontal line of the barrel in the parallel node (dead spot) and continue into the part cycle at the muzzle barrel.

From Figure 6 we can see that when we start at the end of the barrel, where is the barrel fixed we have one long cycle, which goes into the parallel node. Then from this parallel node start a partial cycle at the muzzle barrel. The important is, to make the partial cycle least as possible, and the barrel will be having during shooting a smaller yaw.

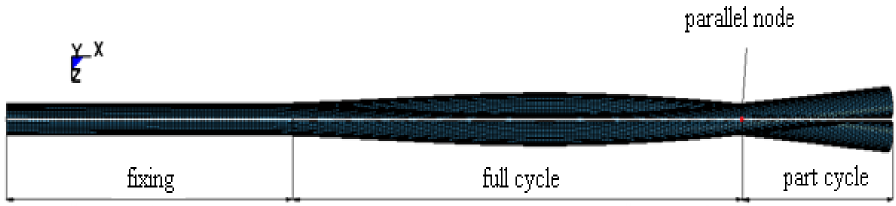

Fig. 6. Behaviour the second eigenmode for cylindrical barrel

The results of numerical modal analysis for cylindrical and conical barrels and their modifications: with and without muzzle break, without and with slots which are flatter or deeper under 45^o from axis y or direct from axis y i.e. 90^o are listed in Tables 3, 4 and displayed in Figure 7-10. In Tables 3-5 the abbreviations means: MB – muzzle break, F 45^o- flatter slots under appropriate angle, D – deeper slots (or double deeper as F) slot and T – very deep slots (or triple deeper as F).

From Table 3 is evident, that the full cylindrical barrel (Cyl) with and without the barrel muzzle and with 90^o slots vibrate horizontally. When this barrel will has four slots flatter or deeper under angle 45^o, the barrel with these configurations change the direction of vibrate from horizontally (axis x) to vertically (axis y). Also from Table 3 is evident that natural frequencies for both Cyl F 45^o and Cyl F 90^o are the same also for both configurations with muzzle break Cyl F 45^o MB and Cyl F 90^o MB are the same. But while configurations with 45^o slots vibrate in axis y, configurations with 90^o slots vibrate in axis x. The cylindrical barrel with the very deep slots at 45^o with the muzzle break, in Table 3 – Cyl F 45^o T MB, changes direction of vibration to y 45^{o}r.

Modal analysis for both all the barrel configurations was solved thus that slots were made from the barrel outer diameter to the barrel wall deeper. Therefore, the full cylindrical or conical barrel has the highest natural frequencies from their next modifications. From Figure 7-8 we can see the course of the frequencies versus modes where for the comparison in these figure is also stated the frequencies for the full cylindrical barrel with and without the muzzle break.

Table 3. Natural frequencies and corresponding mode shapes for cylindrical barrels

Barrel/ Mode	**Cyl**	**Cyl MB**	**Cyl F 45º**	**Cyl F 45º MB**	**Cyl F 45º D**	**Cyl F 45º D MB**
1.	17.48/x	13.75/x	16.99/y	13.09/y	16.83/y	12.63/y
2.	108.74/x	89.26/x	105.86/y	86.23/y	104.86/y	84.45/y
3.	300.91/x	253.18/x	293.14/y	245,99/y	290.29/y	242.07/y
4.	457.27 ↕	360.25 ↕	439.05↕	334,02 ↕	408.21 ↕	290.29 ↕
5.	580.01/x	496.31/x	565.23/y	483.54/y	559.46/y	476.54/y
6.	739.52 ↔	648.99 ↔	737.1 ↔	638.06 ↔	736.53 ↔	628.2 ↔
7.	939.44/x	813.14/x	915.73/y	793.32/y	905.76/y	701.77/y
8.	1370.5/x	1127.7 ↕	1317.3 ↕	1069,7 ↕	1224.3 ↕	952.82 ↕
9.	1371.8 ↕	1195.8/x	1336.2/y	1167,6/y	1320.5/y	1149.8/y
10.	1864.2/x	1636.4/x	1817.8/y	1598.7/y	1794.9/y	1572.5/y
Barrel/ Mode	**Cyl F 90º**	**Cyl F 90º MB**	**Cyl F 90º D**	**Cyl F 90º D MB**	**Cyl F 45º T**	**Cyl F 45º T MB**
1.	16.99/x	13.09/x	16.7/x	12.61/x	16.82/y	12.71/y45ºr
2.	105.86/x	86.23/x	104.1/x	84.31/x	104.78/y	84.91/ y45ºr
3.	293.14/x	245.99/x	288.28/x	211.72/x	289.8/y	243.09/y45ºr
4.	439.05↕	334.02 ↕	392.64 ↕	289.92 ↕	374.32 ↕	277.2 ↕
5.	565.23/x	483.54/x	555.68/x	475.93/x	557.74/y	477.92/y45ºr
6.	737.1 ↔	638.06 ↔	735.5 ↔	627.75 ↔	736.19 ↔	628.73 ↔
7.	915.73/x	793.32/x	899.7/x	780.93/x	901.45/y	782.93/y45ºr
8.	1317.3 ↕	1069.7 ↕	1177.5 ↕	951.38 ↕	1122.3 ↕	909.24 ↕
9.	1336.2/x	1167.6/x	1311.6/x	1148.71/x	1311.7/y	1144.6/y45ºr
10.	1817.8/x	1598.7/x	1782.7/x	1571.3/x	1779.4/y	1569.4/y45ºr

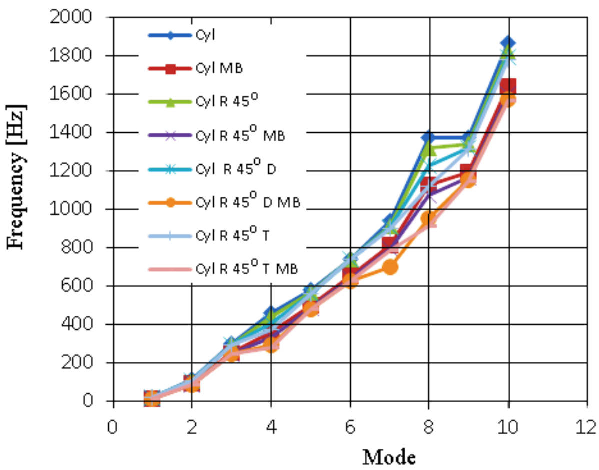

Fig. 7. Natural frequencies vs. modes for cylindrical barrels and fluted cylindrical barrels with four outer slots under 45° from axis y

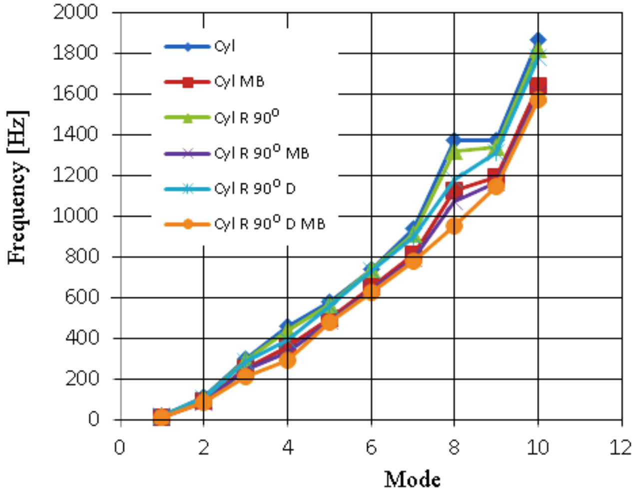

Fig. 8. Natural frequencies vs. modes for cylindrical barrels and fluted cylindrical barrels with four slots layout 90° from axis y

From Table 4 we can see, that the full conical barrel with and without the barrel muzzle vibrate 45° from the left of axis y. Next all its configurations change the direction of vibrate from y45°l to horizontally (axis x). From all these configurations for both barrels we have the scheme how is possible the vibration of the barrel during shooting. Then we have possibility to choose the appropriate configuration with the aim to achieve good accuracy of fire from given weapon system.

Also from Table 4 is evident that natural frequencies for the both Conical F 45° and Conical F 90° are the same, also for both configurations with muzzle break Conical F 45° MB and Conical F 90° MB are the same. Other configurations are almost similar.

From Figures 9-10 we can see the course of the frequencies versus modes where for the comparison in these figure is also stated the frequencies for the full conical barrel without and with the muzzle break. For the conical barrel and its modifications without the muzzle break and also for all the modifications with the muzzle break are small differences between natural frequencies how is apparently from the graph course on Figures 9-10.

When we compare both the cylindrical and conical barrel we can see, that natural frequencies at the conical barrel at the first mode is higher than at the cylindrical barrel. For example, at the first mode is difference 18 %. But at both these ones with the muzzle break is difference very small only 2.55 %.

However, when we compare the second mode, we can see that the natural frequencies for the cylindrical barrel is higher than for the conical one. For the cylindrical barrel without the muzzle break is higher about 1.39 % and with the muzzle break is also higher about 11.08 % etc.

Table 4. Natural frequencies and corresponding mode shapes for conical barrels

Barrel/ Mode	Conical	Conical MB	Conical F 45°	Conical F 45° MB	Conical F 45°D
1.	21.33/y45°l	14.11/y45°l	20.72/x	13.34/x	20.51/x
2.	107.23/ y45°l	79.37/y45°l	104.58/x	77.01/x	103.62/x
3.	279.14/ y45°l	219.97/y45°l	272.6/x	214.88/x	270.16/x
4.	529.93/ y45°l	336 ↨	517.84/x	307. 9 ↨	513.11/x
5.	584.7 ↨	431.92/y45°l	562.1 ↨	422.73/x	526.7 ↨
6.	857.46/ y45°l	682.68 ↔	835.32/x	667.08 ↔	827.34/x
7.	865.74 ↔	707.95/y45°l	864.13 ↔	693.34/x	863.16 ↔
8.	1245.9/ y45°l	1001.4 ↨	1218.4/x	968.44 ↨	1206.1/x
9.	1424.9 ↨	1040/y45°l	1378.4 ↨	1019/x	1298.8 ↨
10.	1697/y	1421.8/y45°l	1660/x	1394.2/x	1642.1/x
Barrel/ Mode	**Conical F 45° D MB**	**Conical F 90°**	**Conical F 90° MB**	**Conical F 90° D**	**Conical F 90° D MB**
1.	12.96/x	20.72/x	13.34/x	20.47/x	13.11/x
2.	76.13/x	104.58/x	77.01/x	103.38/x	76.08/x
3.	213.17/x	272.6/x	214.88/x	269.6/x	212.55/x
4.	281.74 ↨	517.84/x	307. 9 ↨	512.36/x	301.13 ↨
5.	419.55/x	562.1 ↨	422.74/x	552.98 ↨	418.41/x
6.	656.64 ↔	835.32/x	667.08 ↔	826.83/x	664.56↔
7.	687.83/x	864.13 ↔	693.35/x	863.91 ↔	686.65/x
8.	915.43 ↨	1218.4/x	968.41 ↨	1206.6/x	954.84 ↨
9.	1010.4/x	1378.4 ↨	1019/x	1357.9 ↨	1009.9/x
10.	1381.8/x	1660/x	1394.3/x	1644.7/x	1382.7/x

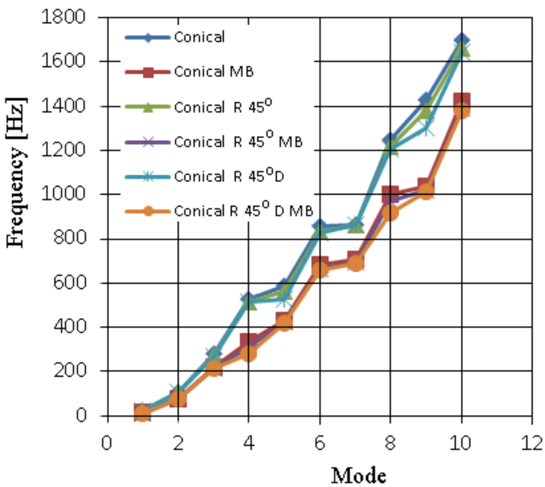

Fig. 9. Natural frequencies vs. modes for conical barrels and fluted conical barrels with four outer slots under 45° from axis y

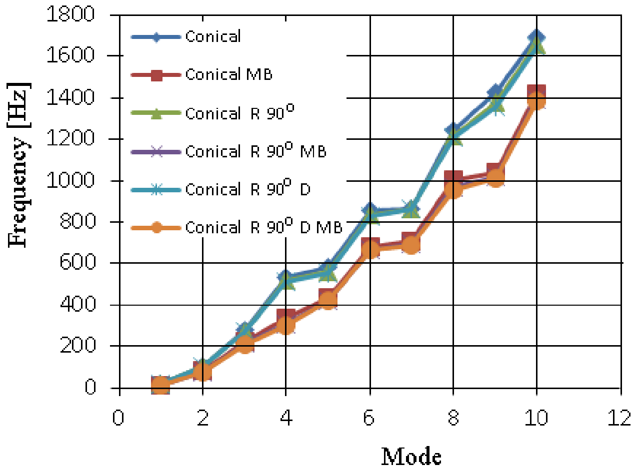

Fig. 10. Natural frequencies vs. modes for conical barrels and fluted conical barrels with four slots layout 90° from axis y

How was stated earlier, when is to the barrel muzzle something attached the natural frequencies fall down. For this case we can better fixing the barrel mainly its muzzle how is shown in Figure 3. In Table 5 are listed natural frequencies for the cylindrical barrel configuration with the armature. The configuration A1 means cylindrical barrel design with four slots layout 45° from axis y with fixing, muzzle break and armature, which has outer diameter 130 mm at the weapon case and its thickness is 2.5 mm. The armature is fixed to the barrel near the muzzle break with a mount.

The configuration A2 is the same barrel but has the bigger armature i.e. outer diameter is 260 mm at the weapon case and thickness of the armature is 3.5 mm. From Table 5 we can see the big differences between the thinner armature A1 and thicker A2. The natural frequencies are very higher than at all other configuration the both barrel. Definitely the armature A2 will has bigger weight so at selection we have to proceed carefully and choose right configuration to get good accuracy of the weapon system. In Table 5 an abbreviation A means the natural frequencies for the armature. At these natural frequencies the muzzle barrel shows an insignificant motion. In Figure 11 are shown modal shapes of cylindrical barrel with armature and muzzle break for configuration A1.

Table 5. Natural frequencies and corresponding mode shapes for cylindrical barrels with armature

Barrel/ Mode	Cylindrical F 45° D A1	Cylindrical F 45° D MB A1	Cylindrical F 45° D A2	Cylindrical F 45° D MB A2
1.	23.82/y	18.83/y	52.29/y45°r	43.05/y45°r
2.	102.54/y	88.9/y	109.34/y	94.86/y
3.	224.68/y	217.18/y	248.89 A	249.67 A
4.	267.72 A	256.28/y	286.26/y	249.87 A
5.	268.88 A	267.82 A	325.58/x	254.68/y
6.	282.18/y	267.94 A	389.84 A	322.84/xs
7.	377.87 A	348.27 ↕	549.5/y	392.79 A
8.	378.1 A	378.01 A	556.39 ↕	393.51 A
9.	432.7 ↕	378.18 A	611.83 A	475.58 ↕
10.	541.34/y	483.16/y	641.81 A	498.87/y

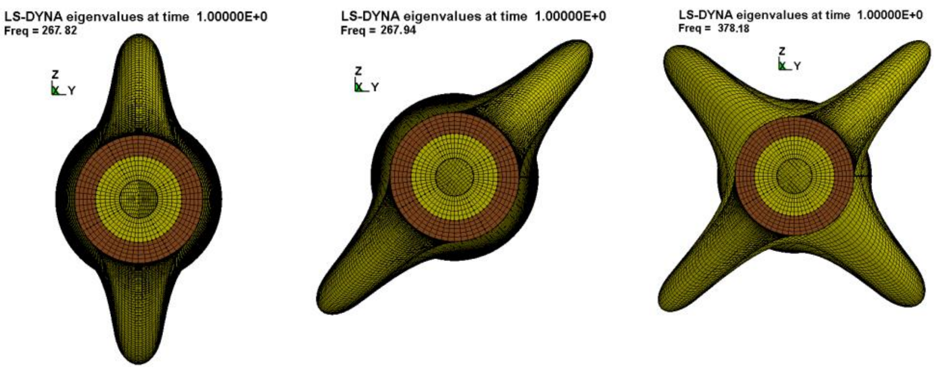

Fig. 11. Modal shapes of cylindrical barrel with armature and muzzle break (A1)

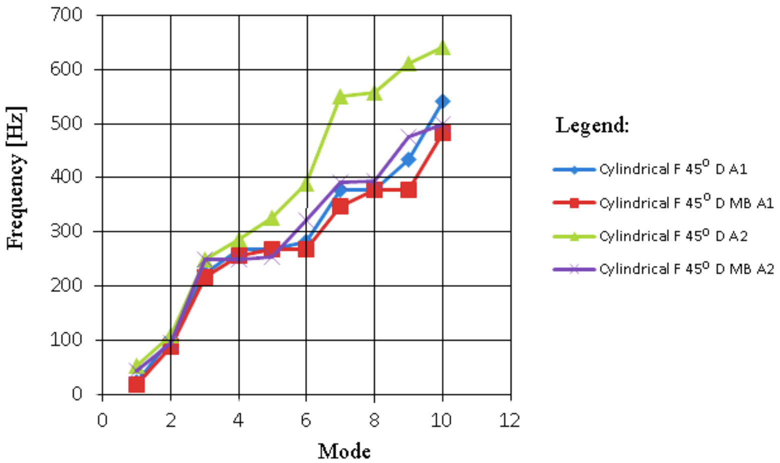

Fig. 12. Natural frequencies vs. modes for fluted cylindrical barrels with four outer slots under 45° from axis y and armature

3. CONCLUSION

On the base of the simulation results we can use some design corrections for this type of weapon with aiming to improve the initial vibration which has influence to weapon´s firing accuracy. We know that modal analysis assumes the structure vibrates in the absence of any excitation and damping. In spite of that a real structure has an infinite number of the natural frequencies which have a discrete mode of the vibration. Each mode corresponds to the situation where elastic forces are cancelled with inertial forces.

The mode of the vibration may be seen as the shape of the structure that leads to the cancellation between inertial and stiffness forces for the given frequency of the vibration. In the reality, the damping controls the stiffness of the structure when is in the resonance, but the damping is not modelled in the modal analysis. Nevertheless, the vibration analysis by FEM almost always starts with the modal analysis. The modal analysis provides important results which can be also used as inputs for other types of the vibration analysis.

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