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Dynamic Analysis of Co-Axial Non-Synchronous Rotating Assembly of Horizontal Decanter Centrifuges

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Abstract
In most of industrial works, merged solid and liquid phases as a single mixture must be separated to different phases. A centrifuge is a device that separate components of different densities using high rotational speed. The decanter centrifuge, which separates continuously solid materials from liquids in the slurry, has become a major processing tool in a wide range of liquid-solid separation applications. The main rotating assembly of decanter centrifuge consists of two co-axial non-sinchronous rotors, namely: the bowl and the scroll (conveyor). To determine the solid content in the outfeed, there is a differential speed between the decanter bowl and the scroll. The crucial part of mechanical design of a decanter centrifuge is dynamic analysis of rotating assemblies to meet the rotordynamics requirements. In this research dynamic analysis of the finite element model of a horizontal decanter centrifuge, which has been lead to design and build a successfully tested machine, is presented. The comparison of experimental values and numerical simulation shows that the presented finite element model is reliable to design of new horizontal decanter centrifuges, according to the purchaser request and separation operation demands.

Keywords: Dynamic analysis, Horizontal decanter centrifuge, Finite element method.

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Introduction

The decanter centrifuge has become the very dependable machine of a wide range of liquid-solid separation activities. It is widely used as a most valuable device in combating environmental pollution to dewater the waste sludges. The decanter operates by sedimentation, a process causing the separation of suspended solids by virtue of their higher density than the liquid in which they are suspended. Generally, the difference in density or the particle size are small, so the separation force must be increased by the imposition of centrifugal forces many times of gravity alone. The major advantage of the decanter in the spectrum of sedimentation equipment is its ability to separate on a fully continuous operation.
As a complicated piece of machinery, the decanter comprises a solid cylindrical bowl, rotating at high speed. Inside the bowl is a scroll (screw conveyor) rotating at a slightly different speed. The differential speed between bowl and scroll provides the conveying motion to collect and remove the solids, which accumulate at the bowl wall. A slurry of liquid and suspended solids is fed along the centre line to some fixed position within the bowl, and is accelerated outwards to join the pond of liquid held on the bowl wall by the centrifugal force. This same force then causes the suspended solids to settle, and accumulate at the bowl wall. The clarified liquid then flows along the bowl, to leave at one end of it, over some kind of weir design, which sets the level of the liquid surface in the bowl. The other end of the bowl is sloped inwards, towards the centre, thus providing a beach, up which the solids are conveyed, to be discharged from the bowl, at the top of the beach. Whilst the solids are conveyed up the beach, some, hopefully most, of the entrained liquid drains back into the pond, to join the liquid flow towards the far end. The scroll usually is carried on a hollow axial hub, through which the slurry feed tube passes to the feed zone. The diameter, the number, and the pitch of the conveyor flights are chosen to match the needs of the slurry being treated as are the depth of the pond, the length of the bowl, the conveyor differential speed, and the angle of slope of the beach. Most decanters operate with their axis horizontal, in which case they usually are mounted in substantial bearings at each end of the bowl. Vertical operation is possible, in which case the bowl is carried only on one set of bearings, at the top. If the decanter is short, then cantilevered horizontal operation is also possible, with bearings at one end only. The rotating bowl is enclosed in a casing, which is divided to ensure that the discharged liquid (the "centrate") and solids cannot remix after separation. The basic decanter is completed with a drive motor, usually electrical, and a gearbox, which controls the differential speed of the conveyor [1], [2]. (See Figure 1).

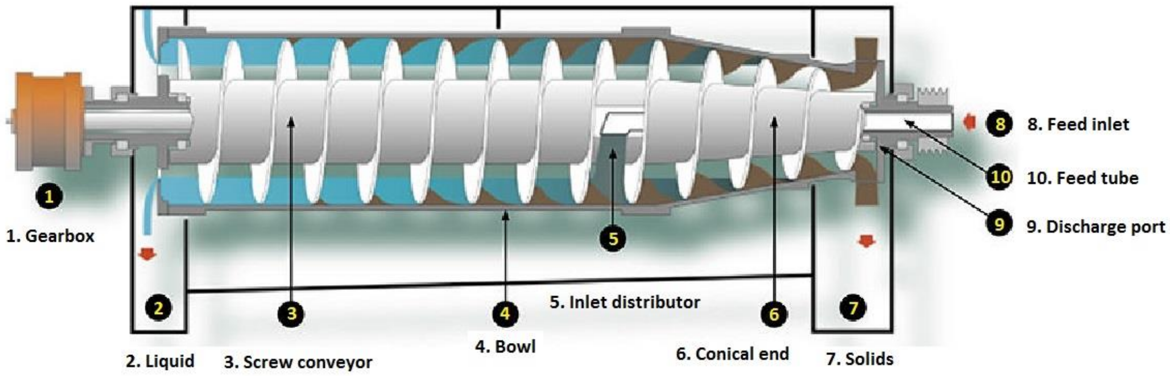


Figure (1) The main parts of a decanter centrifuge

In the general field of rotor dynamics, the study of dual and multi-rotor systems is less well covered than the mono rotor type - but there are a few references on recent work. Co-axial dual rotor systems that have been studied [3], [4], [5], include simplifying assumptions or exclusions using the non-realistic models. Bonello’s and Hai’s [6] focused on lateral bending of the dual rotors of an aircraft engine, considering linear characteristics in the supporting bearings. A simple dual rotor model with rigid bearings to demonstrate analytical procedures studied by Lalanne and Ferraris [4]. Kamenicky [7], and Hai and Bonello [8], analysed the decanter centrifuge rotors assuming simply supported linked shafts. They showed that the response of the auger conveyor is dependent upon its mounting to the hubs of the outer rotor, the bowl assembly, and the degree of residual unbalance. The nonlinear aspects of rolling element bearings on the motion of the conveyor in response to unbalance have been investigated in [9], [10], [11].
Machines that are designed using sophisticated computer-aided engineering methods will be less problematic than machines designed without the benefit of such analysis. Even if the purchaser of rotating equipment contracts the

vendor to perform mechanical acceptance tests prior to delivery and installation the discovery of design-related problems during these tests will likely compromise the planned cost of the unit and/or its delivery schedule. For this reason, specifying a mechanical acceptance test without also requiring a design analysis and review prior to construction may force a purchaser to accept equipment that will prove problematic after installation.
The American Petroleum Institute's Subcommittee on Mechanical Equipment has produced a series of specifications that define mechanical acceptance criteria for new rotating equipment. Experience accumulated by purchasers over the past ten years indicates that if the standards are properly applied, the user can be reasonably assured that the installed unit is fundamentally reliable and will, barring problems with the installation and operator misuse, provide acceptable service over its design life. This research presents dynamic analysis of the finite element model of a horizontal decanter centrifuge, which has been lead to design and build a successfully tested horizontal decanter centrifuge in Hamgam Sanat Co., Tehran, Iran (Figure 2). The comparison of experimental values and numerical simulation shows that the presented finite element model is reliable to design of new horizontal decanter centrifuges, according to the purchaser request and separation operation demands.

Figure (2) Courtesy of Hamgam Sanat, Tehran, Iran

Result Discussion

Decanter centrifuges should be designed to operate classically stiff. It means that the first dry critical speed must be above the decanter centrifuge's maximum continuous speed by the following:

- 20% for rotors designed for wet running only
- 30% for rotors designed to be able to run dry

According to most of standards, if a rotor be classically stiff, lateral vibration analysis is not needed. So, finding critical speed of a rotor is a crucial stage of design of rotating equipment.
From the physical dynamics point of view, the centrifuge consists of rotating and stationary assemblies, that centrifuge's rotating assembly has two main components; the bowl assembly and the conveyor, as shown in Figures 3-5, who's individual and joint responses determine the state of vibration of the machine under operating conditions.

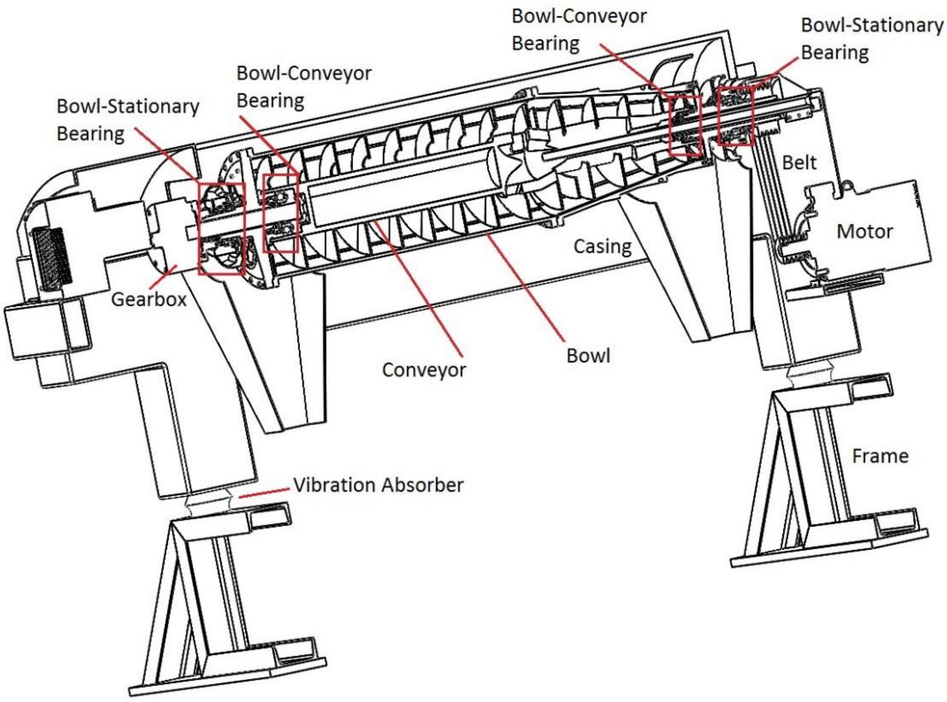


Figure (3) rotating and stationary assemblies of decanter centrifuge

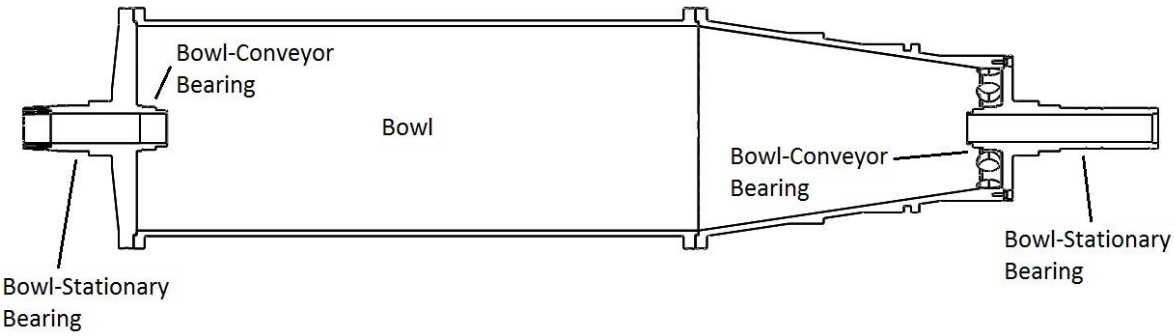


Figure (4) rotating bowl assembly

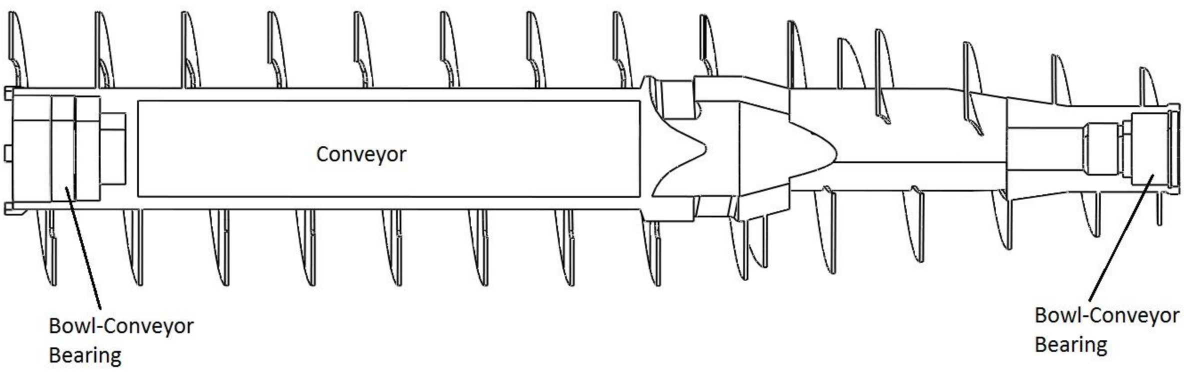


Figure (5) rotating conveyor stationary assembly

The bearings are the components that make the greatest contribution to the rotor responses however, as they determine the boundary conditions of restraint. In addition to shaft properties, dynamic behavior of a rotor is dependent on bearings stiffness and bearings damping. As a valid concept, a bearing can be represented by eight springs and dampers in a linearized model to describe the eight conventional stiffness and damping coefficients as shown in Figure (6) where the K_{ii} and C_{ij} are called the linearized stiffness and damping coefficients, respectively. The first subscript indicates the direction of the force acting on the bearing surface, and the second one corresponds to the direction of displacement or velocity, for example, in a journal bearing, K_{yz} corresponds to a stiffness produced by a fluid force in the y-direction due to a rotor displacement in the z-direction. The coefficients K_{ii} and C_{ii} are known as the direct stiffness and damping, respectively, while K_{ij} and C_{ij} are referred as cross-coupled ones. Although journal bearings have all eight coefficients, roller bearings are represented only by direct terms, K_{ii} and C_{ii}. The dynamic coefficients for all bearings can be calculated using computer programs designed for this purpose. In this research, all used bearing coefficients have been considered as constant values [12].

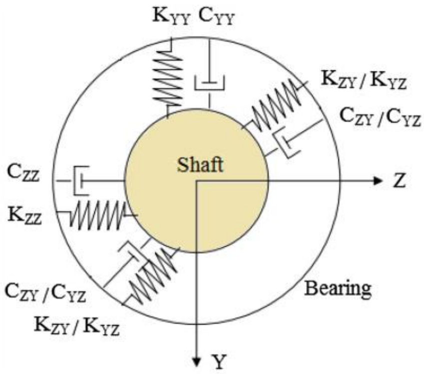


Figure (6) Dynamic properties of a bearing

Analysis of the rotating system must include the dynamic performance of the bearings. In this respect, the rotors of the decanter centrifuge are each simple systems, which the complexity lies in their co-axial combination. At first, it is necessary to identify natural frequencies to assess their importance in relation to the normal operating speeds and determining the response to unbalance. Increasingly, new industrial designs are subjected to modeling and numerical analysis using finite element analysis (FEA) in order to be confident that manufacture can proceed. However, in both design and diagnostics the analysis of the problem is constrained by the information available at the time and the knowledge of the engineer/diagnostician. Therefore, the major components of the rotating assembly were prepared in Solid Works and exported to ANSYS Workbench, where the finite element model has been studied.
Figure (6) shows a schematic dynamical representation of the two-rotor system of the horizontal decanter centrifuge.

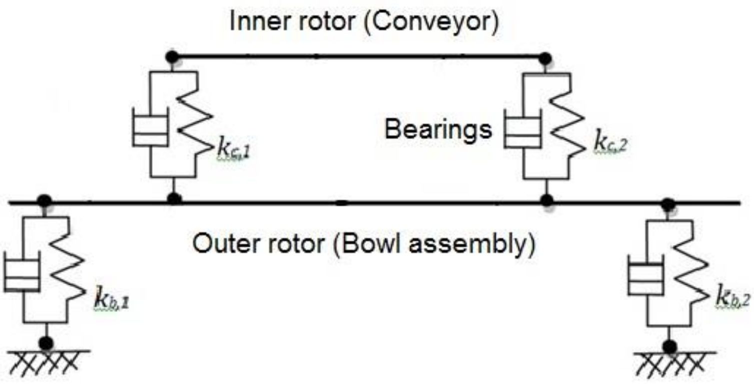


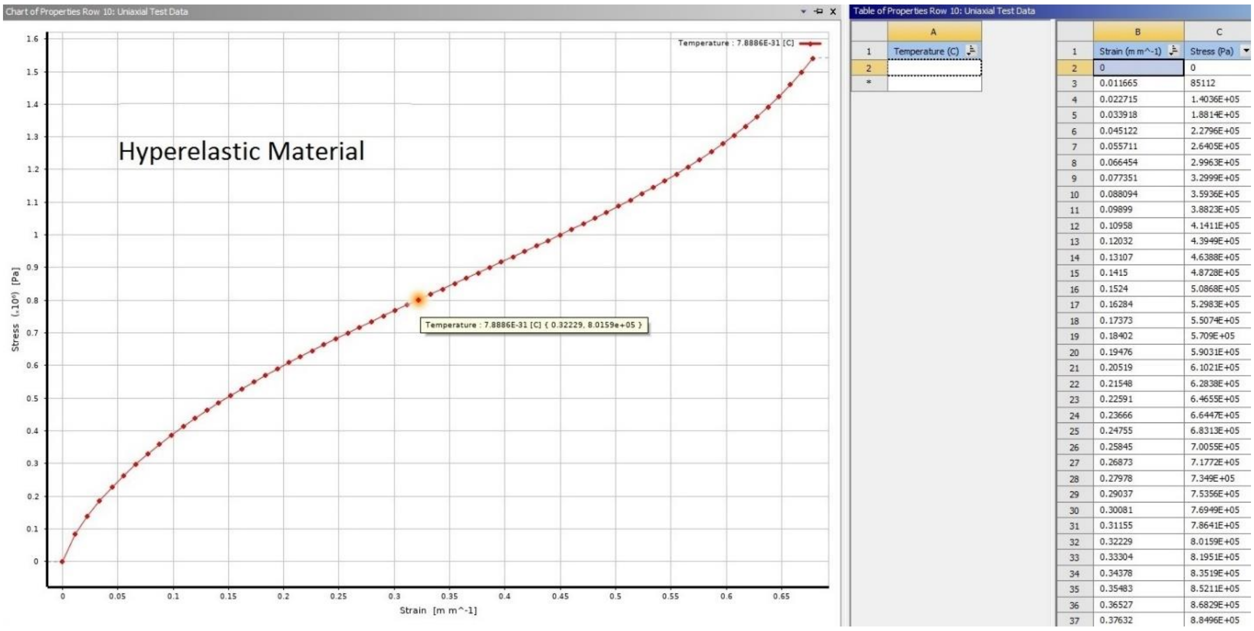
Figure (7) A schematic dynamical representation of the two-rotor system

In general terms, the matrix equations of motion of each rotor system will be in the form:

$$[M]\{\ddot{q}\} + ([C] + [G])\{\dot{q}\} + [K]\{q\} = \{Q\}$$

Where
[M] = mass matrix
[K] = rotor stiffness matrix
[C] = damping matrix
[G] = skew symmetric gyroscopic matrix
{Q} = column vector of loads
{q} = column vector of generalized nodal displacements

The finite element model prepared and analyzed in ANSYS considering the major items. The effects of vibration absorbers on dynamic behavior of rotor-bearing systems are considerable, so, at first, dynamic properties of them must be obtained. As shown in Figure (8), Stress-Strain relationship of the vibration absorbers, which comprise hyperelastic material and have complex non-linear behavior, with the hardness of Shore-A 80 (a kind of rubber), have been extracted experimentally.



	B	C
1	Strain (m m^-1)	Stress (Pa)
2	0	0
3	0.011665	85112
4	0.022715	1.4036E+05
5	0.033918	1.8814E+05
6	0.045122	2.2796E+05
7	0.055711	2.6405E+05
8	0.066454	2.9963E+05
9	0.077351	3.2999E+05
10	0.088094	3.5936E+05
11	0.09899	3.8823E+05
12	0.10958	4.1411E+05
13	0.12032	4.3949E+05
14	0.13107	4.6388E+05
15	0.1415	4.8728E+05
16	0.1524	5.0868E+05
17	0.16284	5.2983E+05
18	0.17373	5.5074E+05
19	0.18402	5.709E+05
20	0.19476	5.9031E+05
21	0.20519	6.1021E+05
22	0.21548	6.2838E+05
23	0.22591	6.4655E+05
24	0.23666	6.6447E+05
25	0.24755	6.8313E+05
26	0.25845	7.0055E+05
27	0.26873	7.1772E+05
28	0.27978	7.349E+05
29	0.29037	7.5356E+05
30	0.30081	7.6949E+05
31	0.31155	7.8641E+05
32	0.32229	8.0159E+05
33	0.33304	8.1951E+05
34	0.34378	8.3519E+05
35	0.35483	8.5211E+05
36	0.36527	8.6829E+05
37	0.37632	8.8496E+05

Figure (8) Stress-Strain relationship of the vibration absorbers

To obtain dynamic properties of vibration absorbers, 3D model of them considering their material properties, as expressed in the explanation of Figure (8), have been imported in ANSYS Workbench. Figure (9) shows the meshed model of vibration absorber in ANSYS. Mechanical analysis of the vibration absorbers as displayed in Figure (10), yields the results, which are used as the input data in rotor-bearing system analysis as presented in the following section.

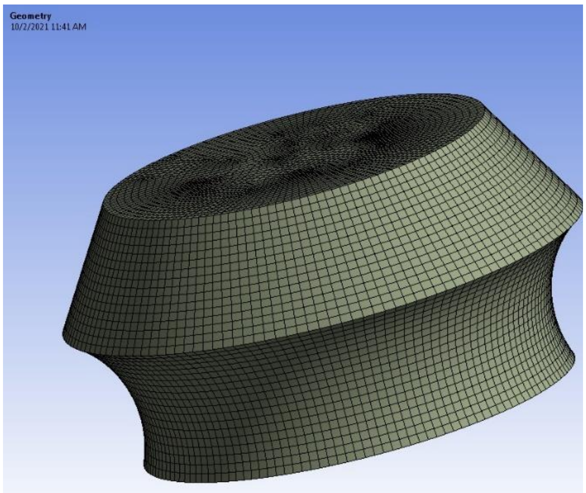


Figure (9) The meshed model of vibration absorber

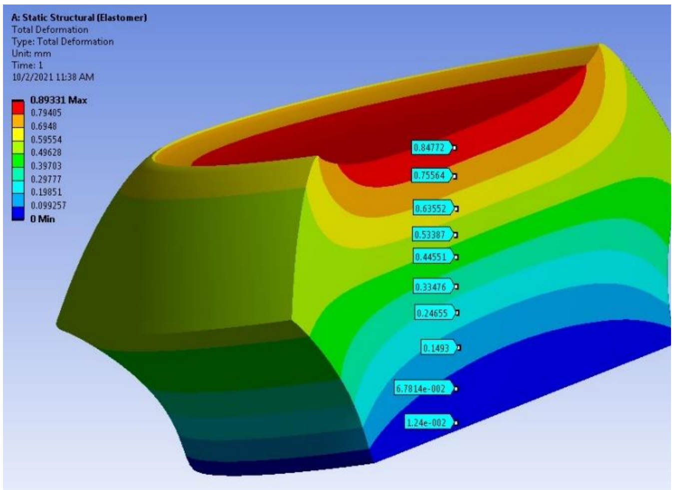
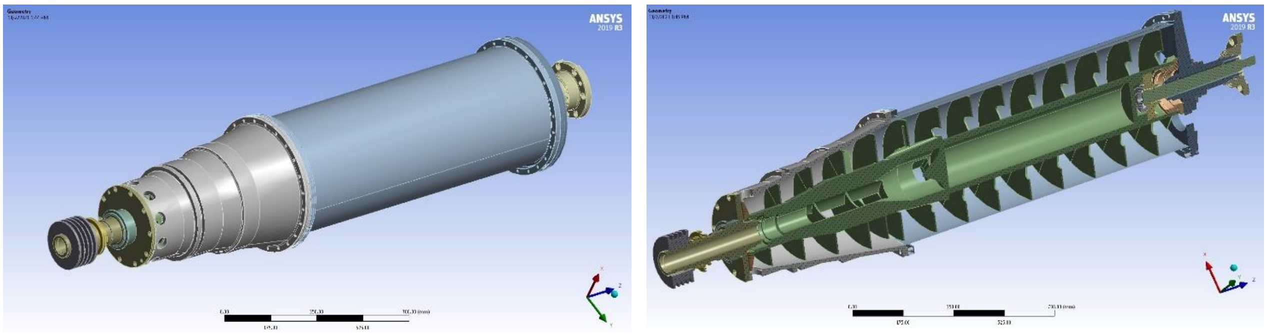


Figure (10) Mechanical analysis of the vibration absorber

As expressed before, the crucial stage of dynamic analysis of co-cxial rotating assembly of decanter centrifuges is modal analysis to find the critical speeds and the mode shapes. As shown in Figure (11), the co-axial non-synchronous rotating assembly of decanter centrifuges has beem imported in ANSYS.



(a) **(b)**

Figure (11) (a) Co-axial non-synchronous rotating assembly of decanter centrifuges, (b) Section view

Figure (12) shows the meshed model of the co-axial non-synchronous rotating assembly of decanter centrifuges in ANSYS.

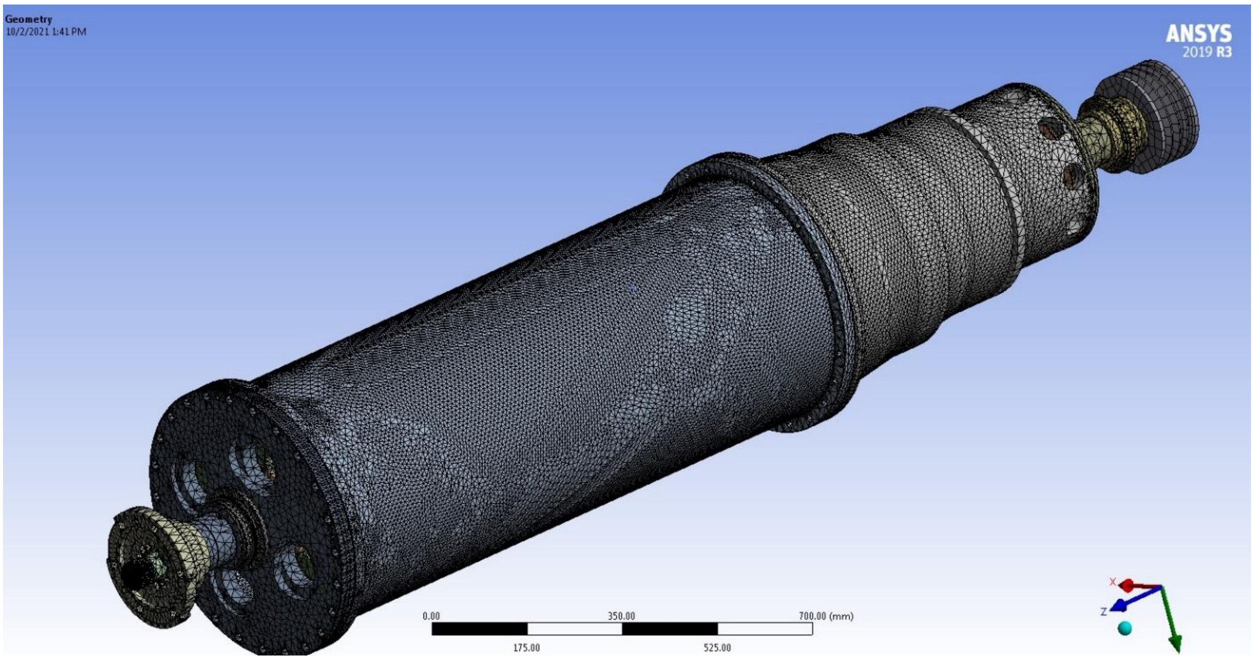


Figure (12) shows the meshed model of the co-axial non-synchronous rotating assembly of decanter centrifuges

The quality of meshing and the skewness of meshed model have been surveyed, as displayed in Figure (13). Indeed, the less skewness, the more mesh quality. The number of elements has been selected to achieve acceptable convergence, where the calculated values improved unimportantly due to more increase in the number of elements.

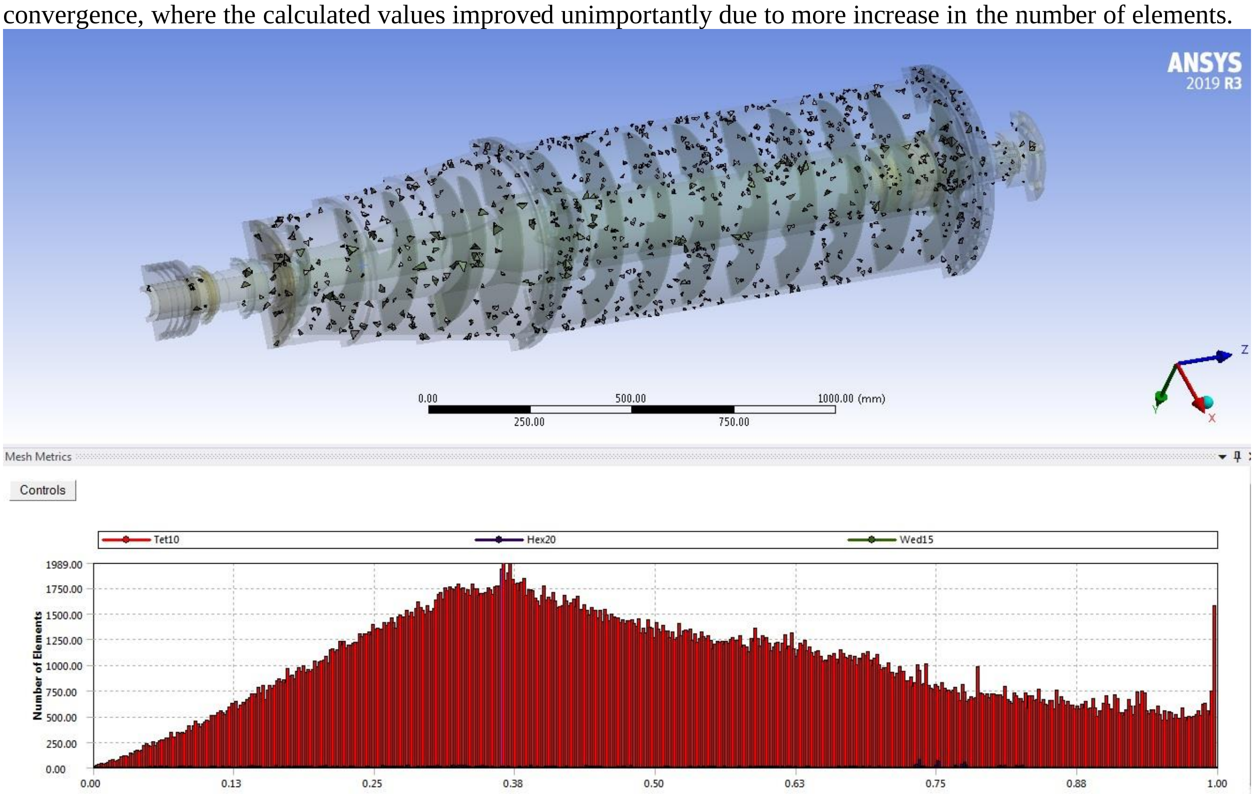


Figure (13) Using the skewness option to examine mesh quality

The first two lateral natural frequencies of bowl assembly and conveyor have been shown in Figure (14). The lowest natural frequency has been obtained 77 Hz, which its mode shape is shown in Figure (14-a). So, the rotating assembly can be regarded as a classically stiff rotor as introduced before, because the decanter centrifuge's maximum continuous speed is 54 Hz. Although there is a difference between natural frequencies and critical speeds, the obtained critical speeds from Campbell diagram, as shown in Figure (15), can also verify this consequence.

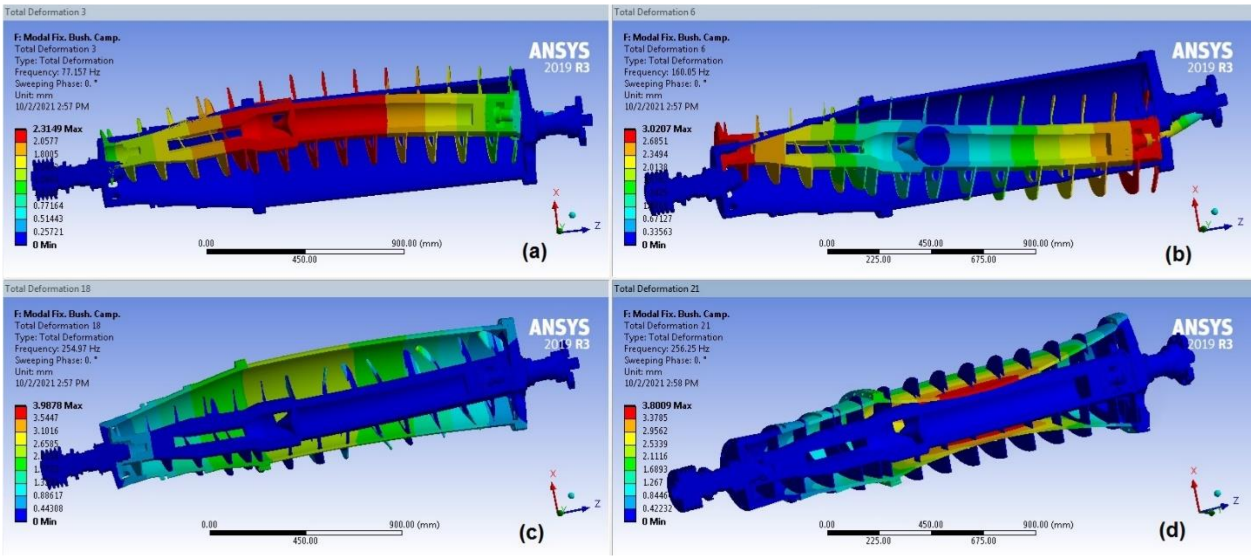


Figure (14) The mode shapes of first two lateral natural frequencies of bowl assembly and conveyor

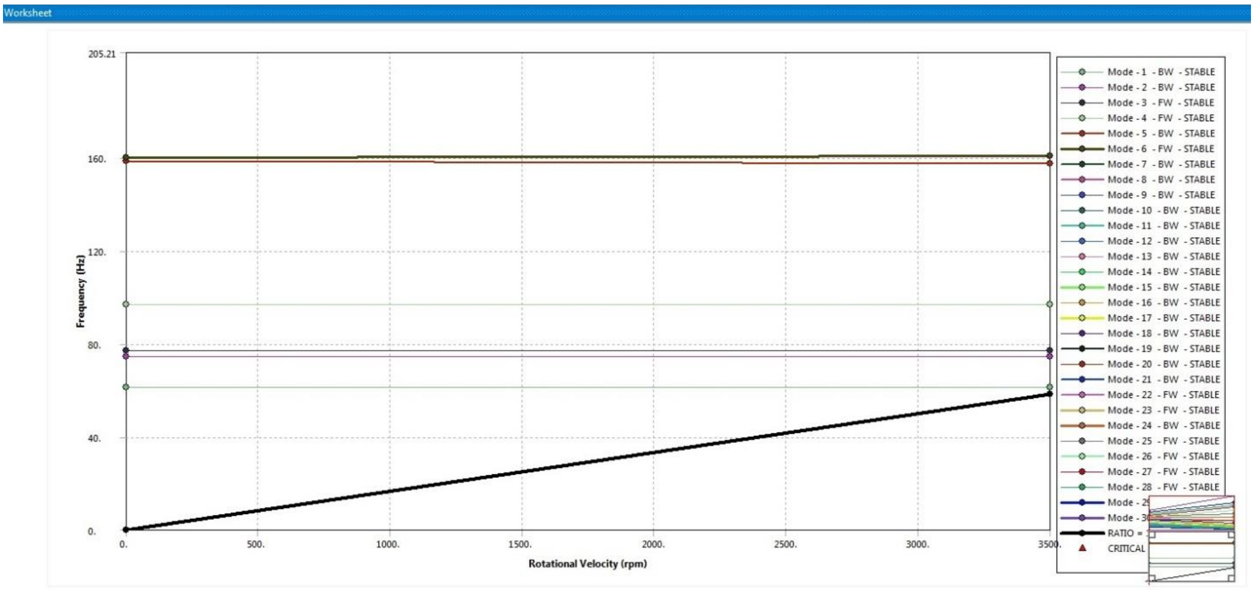


Figure (15) Campbell diagram of rotating assembly

Another requirement that must be taken into account is obtaining the maximum deflection of the inner rotor (conveyor) due to unbalance, to predict the probability of bowl-conveyor contact. As shown in Figure (16), the conveyor has been analysed separately. The amplitudes of conveyor's deflection due to the maximum allowable unbalance according to balance quality grade G 2.5 (ISO-1940-1), has been applied in the middle of rotor and the frequency response has been captured as shown in Figure (17).

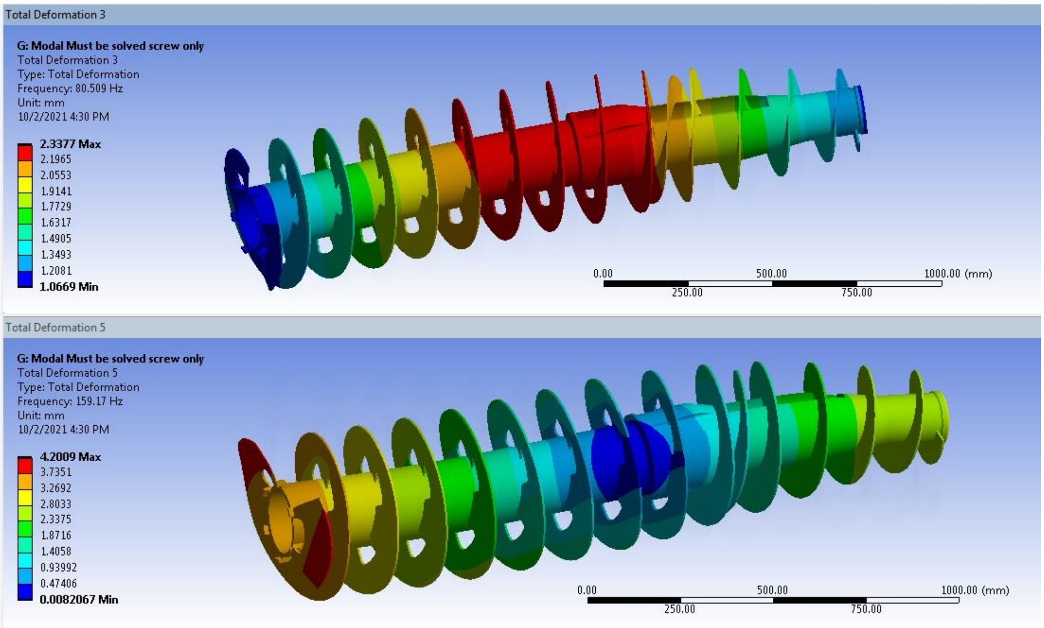


Figure (16) The mode shapes of first two lateral natural frequencies of only conveyor

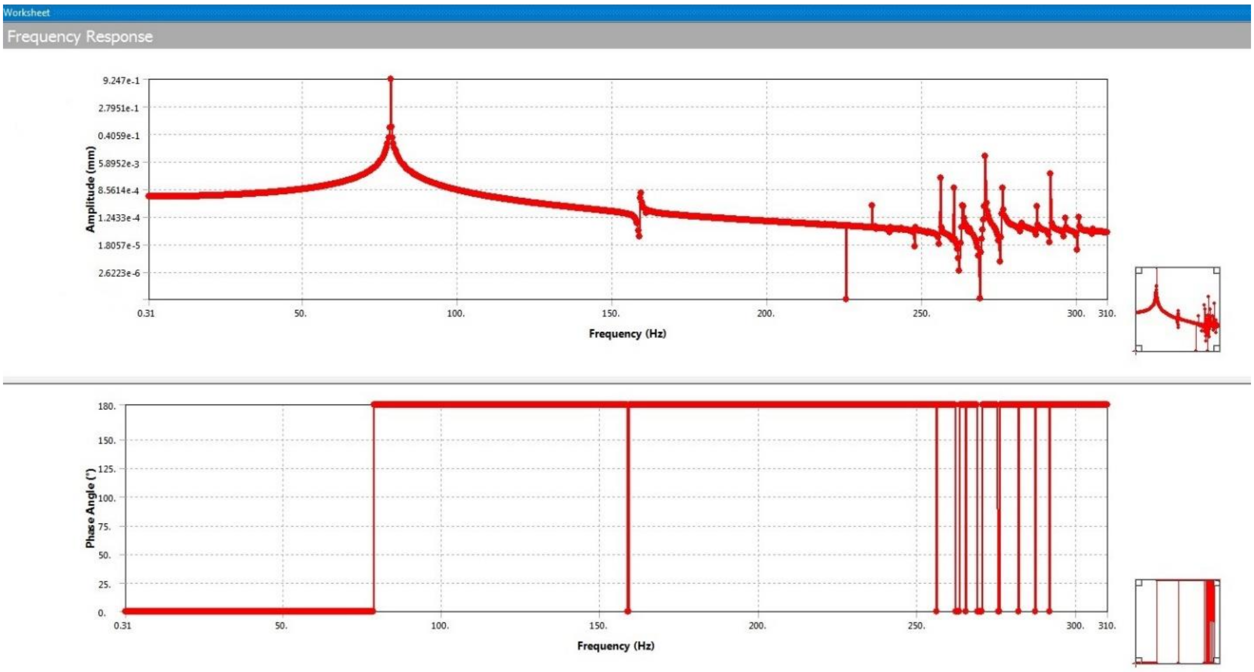


Figure (17) Harmonic analysis and frequency response to maximum allowable unbalance

The final stage is modal analysis of stationary assembly to assure that there are acceptable margin between the continuous speed of decanter centrifuge and natural frequencies of stationary assembly. As shown in Figure (18) there are allowable marging between the continuous speed of decanter centrifuge and natural frequencies of stationary assembly.

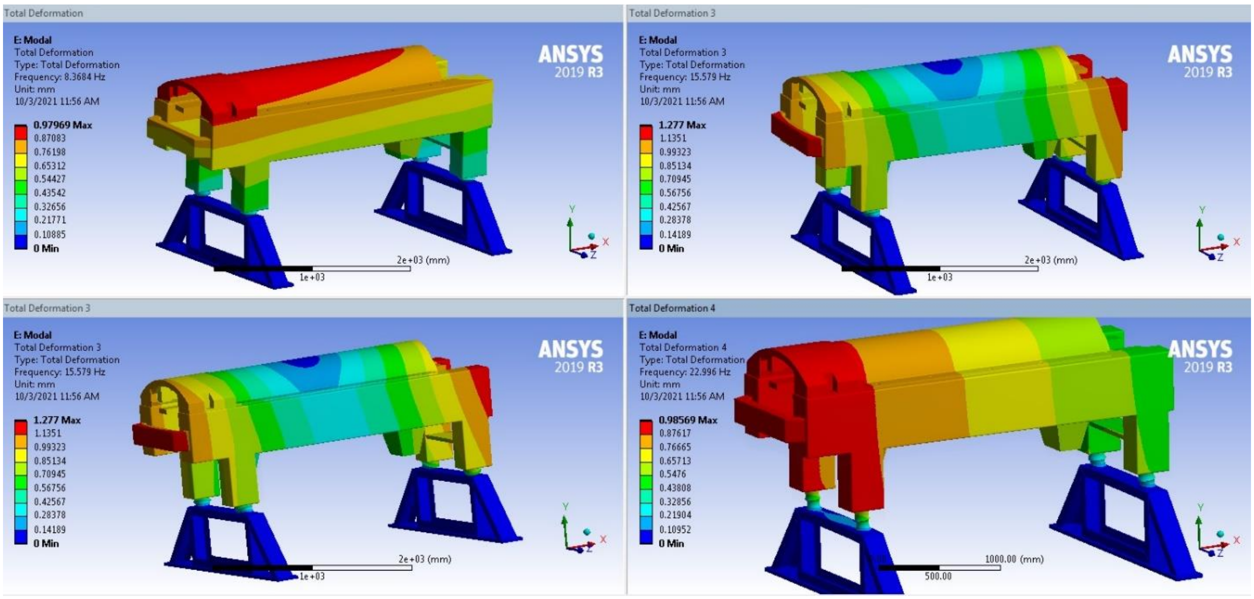


Figure (18) The first four natural frequencies of stationary assembly

The crucial data which was measured was the value of the lowest critical speed. The experimental value of lowest critical speed was 81 Hz, so there are a good agreement between finite element simulation and test data.

Conclusion

The crucial part of mechanical design of a decanter centrifuge is dynamic analysis of rotating assemblies to meet the rotordynamics requirements. In this research dynamic analysis of the finite element model of a horizontal decanter centrifuge, which has been lead to design and build a successfully tested machine, was presented. The comparison of experimental values and numerical simulation showed that the presented finite element model was reliable to design of new horizontal decanter centrifuges, according to the purchaser request and separation operation demands. There was a good agreement between finite element simulation and test data.

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