Vibration analysis of a hydraulic cylinder – a review

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***Abstract* – Hydraulic cylinders are one of the most important components of the hydraulic systems used in a different industrial application. Design of a hydraulic cylinder consists of a different loading and boundary conditions. Vibration of the cylinder during working condition is one of the most crucial elements of the failure criterion .This paper deals with the vibration analysis of the hydraulic cylinder under variable loading application and different boundary conditions. The main cause of the vibration in hydraulic cylinder is stick-slip phenomenon between piston and cylinder which is also responsible for the failure of a sealing material and reduces the fatigue life as well the performance of the hydraulic system. Vibration analysis can be done by static, dynamic and transient way. The Mode Superposition Method of a transient dynamic analysis is one of the most important methods to predict mode shapes.**

***Index Terms* – Hydraulic Cylinder, Mechanical Vibration, Finite Element Method, Dynamic analysis, Mode shapes**

I. INTRODUCTION

Hydraulic driven working machines are commonplace in the industry of today. Hydraulic cylinders are one of the most common components of the hydraulic systems used in many engineering applications like; automatic manufacturing and montage lines, heavy construction equipments, control systems, sensitive measurement and test systems. The applications can vary from very robust excavators to very precise manufacturing robots but in outline the hydraulic actuators are quite similar in mechanical sense. Hydraulic cylinders are actuation devices that used for producing linear motion in the hydraulic systems and they convert the hydraulic energy of the pressurized fluids into the mechanical energy needed to control the movement of machine linkages and attachments. [1]

Hydraulic cylinders are actuation devices that convert the hydraulic energy of the pressurized fluids into the mechanical energy needed to control the movement of machine linkages and attachments. Hydraulic cylinders are used at high pressures and produce large forces and precise movement. For this reason they are constructed of strong materials such as steel and designed to withstand large forces. The fluid pushes against the face of the piston and produces a force.

Friction plays an important role in dynamical analyses by introducing damping to the system. The very basic friction model is the Coulomb friction where the friction force is dependent only on the contact force. However, in systems as the hydraulic cylinder, the friction force is known to be a function of the sliding velocity thus a dynamical friction model is required to capture the velocity dependent properties. Furthermore the stick–slip phenomenon where the sliding is not continuous is an important factor to take into account. In stick–slip phenomenon the friction alternates between the static friction and sliding friction. Through the stick–slip effect the extension of the cylinder is not continuous and it can induce high stress peaks to the system. The dynamical friction model however is not suitable for initial state computation because of the velocity dependency of the model. Moreover, the dynamical friction model introduces a new variable to the system. Therefore it will be derived a friction model for the initial state computations based on the parameters of the dynamical friction model. [2]

Any motion that repeats itself after an interval of time is called *vibration* or *oscillation*. Vibration deals with the study of oscillatory motions of bodies and the forces associated with them. In recent times, many investigations have been motivated by the engineering applications of vibration, such as the design of machines, foundations, structures, engines, turbines, and control systems. Most prime movers have vibration problems due to the inherent unbalance in the engines. The unbalance may be due to faulty design or poor manufacture. Whenever the natural frequency of vibration of a machine or structure coincides with the frequency of the external excitation, there occurs a phenomenon known as *resonance*, which leads to excessive deflections and failure.Multibody dynamics analysis was originally developed as a tool for modeling rigid multibody systems with simple tree-like topologies, but has considerably evolved to the point where it can handle linearly and nonlinearly elastic multibody systems with arbitrary topologies. It is now used widely as a fundamental design tool in many areas of engineering. [3-4]

II. EXISTING LITERATURE

Anttiylinen et al**.** [5] analyzed a model for a linear hydraulic actuator for multi-body simulations. Translational degrees of freedom and the cylinder chamber pressures had been taken as state variables. During static analysis the chamber pressures were embedded thus resulted in a purely mechanical simulation. In dynamic analysis, chamber pressure was considered as separate variable. The sealing friction was taken into account in both static and dynamic analysis. In the numerical simulations, a monolithic coupling was used to treat with the interaction between the hydraulic fluid in the cylinder chambers and the mechanical system. Thus no constraints were needed. In addition, a sophisticated friction model was implemented thus the key elements of the sliding friction between the cylinder lining and piston had taken into account. From the observation it was found that the proposed element has several benefits compared to the traditional methods for modeling the linear hydraulic actuator. There were no constraints equations involved with the system thus no excessive variables have been needed. It was found during the comparison between the hydraulic cylinder element with the length controlled rod element that during starting and stopping of the movement the cylinder element softens the system. The flow rates and the chamber pressures can be determined by the length change of the cylinder. While on the downside the cylinder element made the differential equations stiffer and effective solution algorithms can been easily found.

L. Tomski et al.[6] studied a hydraulic cylinder subjected to Euler's load in aspect of the stability and free vibrations. The rigidity in the constructional nods realizing the load of the considered system was taken into account in the system. Both rotational and translational springs were applied to the loading nods. Regions of the flexural rigidity asymmetry factor for the piston rod and cylinder, where the system is subject to damage as a result of stability loss, were determined in the frame of numerical research into the hydraulic cylinder. Critical load and characteristic curves were also determined in the plane: load–natural frequency. The boundary problem of the hydraulic cylinder was formulated on the basis of Hamilton‟s principle.

The boundary value of the flexural rigidity asymmetry factor μgr separates two regions. In the first region μa ϵ (0, μgr) the system undergoes damage due to a loss of stability, while in the second region μa (μgr, the system undergoes damage due to material effort. The theory of a double extra strong pipe (Lamé theory) was applied to determine stresses in the part of cylinder filled with liquid as shown in Fig.1. The characteristic curves in the plane load – natural frequency, were plotted in the case of free vibrations. Numerical computations were carried out for different parameters of the system, namely: the flexural rigidity asymmetry factor of the piston rod and the cylinder, the total rigidity factor of the system and the degree of coverage of hydraulic cylinder.

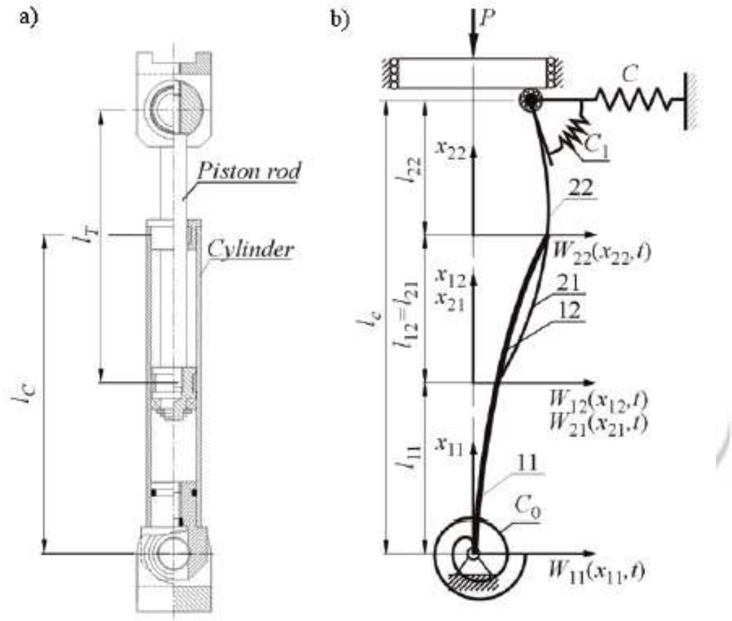

Fig.1 Diagram of the considered hydraulic cylinder:
a) constructional solution, b) mathematical model[6]

M. Stosiak [7] analyzed the vibration insulation of hydraulic system control components. The effects of external mechanical vibrations on hydraulic valves have been considered. A theoretical analysis of the contribution of selected vibration insulators to a reduction in hydraulic valve housing vibrations was carried out. The results of preliminary experimental tests of simple vibration insulators were reported. The Proportional distributor placed in special holder and bilaterally supported with springs, during testing has shown in the Fig. 2.

From the experiment it has been concluded that the use of vibration insulators in the form of springs whose characteristics are linear resulted in a reduction in valve housing vibration acceleration amplitude at certain external vibration frequencies. It can be conducive to resonance at other frequencies. The prepared model and Test were in good agreement at the frequency range between 35 to 60 Hz. the use of a vibration insulator with a nonlinear characteristic the valve housing vibration acceleration amplitude was reduced by a few tens of percent: by over 90% for the vibration insulator with quasi-zero stiffness and by about 80% for the vibration insulator whose stiffness or damping was proportional to displacement or velocity to the second power. A reduction in valve housing vibration will lead to a reduction in slide-valve vibration, particularly in the resonant vibration range.

Fig.2 Proportional distributor placed in special holder and bilaterally supported with springs, during testing [7]

X. Gao et al. [8] analyzed the Static and dynamic analysis of a high static stiffness vibration isolator utilising the solid and liquid mixture. The static analysis was first presented to obtain the stiffness property of the isolator, and it has been found that the isolator exhibits approximately piecewise bilinear stiffness, as a result of which, when subjected to vibration, the isolator operates in the soft stiffness segment, and meanwhile, the stiff segment of bilinear stiffness can ensure the isolator's loading capacity. From the observation concluded that the low operating stiffness of the system resulted in the broader effective isolation frequency band, but high level excitations could result in excessive displacement responses due to the low operating stiffness.

P.J. Gamez et al. [9] used an analytical method based on misalignment to calculate the load capacity of an actuator by determining the critical load (buckling) and limit load (yield stress). Results of maximum load capacity, imperfection angle and experimental work were also calculated for a specific unit of actuator. It has shown from the experiment that imperfection angle and a 5% of wear on the guide ring had reduced the cylinder load capacity by approximately 10% for the tested actuator. Imperfection angle had shown that the effect of fluid compressibility reduced the imperfection angle between rod and cylinder tube. Wear of the guide rings has a major influence on the imperfection angle than that of the radial deformation owing to the internal fluid pressure.

Leone Corradi et al.[10] proposed a procedure for the evaluation of the collapse load of cylindrical shells subject to pressure and axial force, accounting for possibly significant wall thickness. The result was obtained by using the kinematic theorem of limit analysis, which produced the exact result instead of a mere upper bound. A crucial role to one of the end was examined by the assumption of generalized plane strain, imposing that axial strains were uniform without preventing possible elongation of the tube. The assumption was reasonable for long cylinders under axially symmetric loading, since any attempt at possibly non uniform longitudinal strains was contrasted by the adjacent portions and received indirect corroboration by numerical analyses performed on tubes of moderate length, with no a priori enforcement of the constant axial strain condition.

A. Bayon et al. [11] investigated the flexural vibration of cylinders under axial loads as shown in the Fig.3.The flexural vibration of a homogeneous isotropic linearly elastic cylinder of any aspect ratio was analysed. Natural frequencies of a cylinder under uniformly distributed axial loads acting on its bases have been calculated numerically by the Ritz method with terms of power series in the coordinate directions as approximating functions. The natural frequencies of free–free, clamped–clamped, and sliding–sliding cylinders subjected to axial loads were calculated using the proposed three-dimensional Ritz approach and were compared with those obtained with the finite element method and the Bernoulli–Euler theory. It has been concluded that for low compressions the cylinder behaves similarly to a sliding–sliding cylinder, whereas for high compressions the cylinder vibrates as a clamped–clamped one.

Fig.3 Experimental setup of the press and the cylindrical sample [11]

Limit yang et al. [12] analyzed the wave energy converter by incorporating the effect of hydraulic transmission lines dynamically. The wave energy converter system is divided into five subsystems: a heaving buoy, hydraulic pump, pipelines, non-return check valves and a hydraulic motor combined with an electric generator as shown in the Fig.4. A dynamic model was developed by considering the interactions between the subsystems in a state space form. The transient pressures caused by starting/stopping the buoy or closing/opening the check valves were predicted numerically using the established model. The variation of the time-averaged converted electric power with the pipeline length was estimated using the simulation method for the buoy exposed to one irregular sea state. It has been concluded from the simulation that the length of the pipeline will not only affect the amplitude of the transient pressures but also affect the converted power. The applied pipelines could decrease the stiffness of the hydraulic pump system, which caused a phase delay for pumped fluid. It will significantly affect the efficiency of the wave energy converter system. The performance can be improved by employing a hydraulic cylinder with larger diameter, but the structural efficiency is very less in case of a large cylinder diameter.

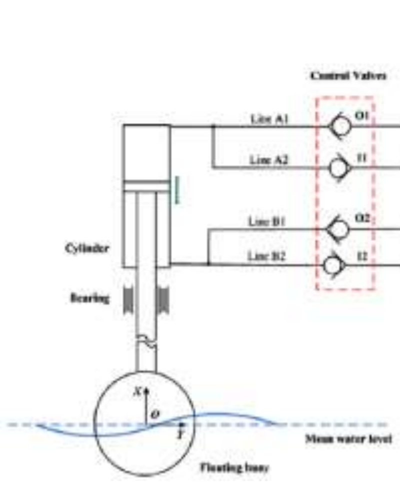

Fig.4. Sketch of wave energy converter consisting of a heaving sphere connected to the hydraulic power take-off [12]

Palu D.L.Mihai [13] carried out the finite element analysis of the hydraulic cylinder of linear hydraulic motor from horizontal Hydraulic Press (Capacity-2 MN). The analysis of the hydraulic cylinder of linear hydraulic motor from horizontal hydraulic Press was made for determination of displacements and deformations. A three-dimensional model of the hydraulic cylinder with a complex geometry was generated based on the designed data. Finite element analysis was performed using COSMOSWorks software as shown in Fig.5. Good agreement between predicted and measured results was obtained for hydraulic cylinder establishing the finite element method as an accurate analysis tool.

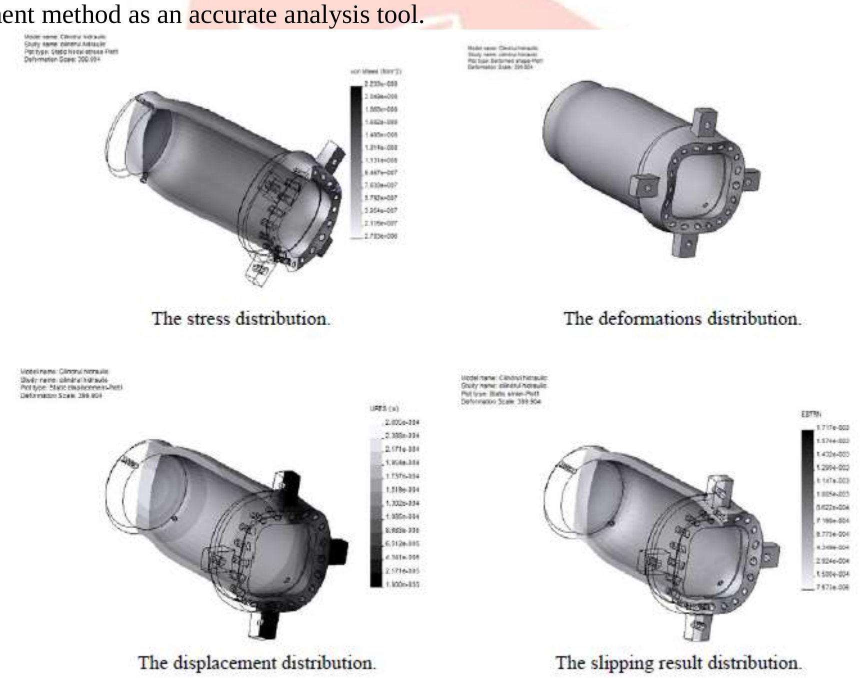

Fig.5 Vibration mode shape of hydraulic cylinder [13]

V. V. Burenin [14] determined mathematical model of the damping properties of hydraulic cylinder through continuity equation and other dynamic forces. Hydraulic cylinders with a piston diameter of 160 mm and a rod diameter of 55 mm were tested using different parameters. Two IRP-1078 rubber packing rings were slipped over each piston and rod of the hydraulic cylinder. The cross-sectional diameters of the rings were 8.5 mm (on the piston) and 5.8 m~ (on the rod). Protective Teflon washers 2 mm thick were m o u n t e d from both sides of each packing ring on the piston and from the one side opposing the action of the pressure exerted by the working fluid on the rod. Deviations in the values of the damping coefficients as computed from equations from experimental values did not exceed 5%. The proposed mathematical model can be used to determine numerical values of the damping coefficients with the hydraulic cylinders operating in a quasi linear regime.

Wojciech Sochackia [15] formulated the problem of damped vibration in hydraulic cylinders on the basis of Hamilton"s principle. The physical model has been taken into consideration the energy dissipation in a vibrating cylinder as a result of external viscous damping and internal damping of viscoelastic material in beams used to construct a model of a cylinder (rheological model by Kelvin–Voigt). Constructional damping in the points of the cylinder connection with the components of the basic structure was also considered. The model is as shown in Fig.6. It has been concluded based on the calculations that as increase in the damping coefficients μ causes faster decay of vibration amplitudes. Loading the system with the force p = 0.3 changes only the damped frequencies, but it did not affect changes in vibration amplitude decay. The introduction of the constructional damping of cylinder vibrations (from mounting parts) causes significant changes in the eigen values of the cylinder. An increase in the damping coefficient μ in the points of mounting causes a constant increase in the damped frequency of vibration. The increase in the value of μ coefficient leads to “locking” the rotational motion in the mounting joints.

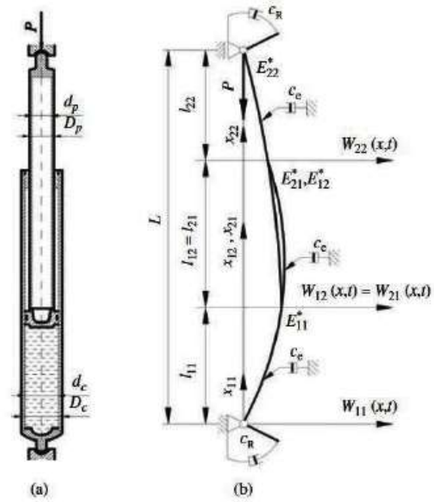

Fig.6. Model Diagram (a) and beam model (b) of a hydraulic cylinder with damping. [15]

Pritish Tapare et al. [16] studied the vibration analysis of a hydraulic cylinder subjected to dynamic loads. Computer aided engineering (CAE) procedures were used to analyze the dynamic response of the cylinder walls. The finite element methods used in the analysis are applied by a computer aided design and analysis software ANSYS. The studies on the moving load were extended to the hydraulic cylinder. An ANSYS APDL code was developed to obtain the time histories of the nodal excitation functions of the pressure loading created by the movement of the piston in cylinder. The mode superposition method was used, which has given the better result for mode analysis. It has been concluded that maximum displacement values increase as the damping values becomes smaller.

N.Upendra et al. [17] carried out the dynamic and static analysis of a composite hydraulic cylinder subjected to pressure by varying fiber orientation and different boundary conditions. Finite element analysis was performed by using the commercial finite element packages. It was found that for 0/90/90/0 fiber orientation has less deflection for carbon/Epoxy made of laminated composite compared with hydraulic cylinder made of steel.

Key-Sun Kim [18] studied to obtain design parameters by magnetic field analysis and vibration mode analysis for a small-sized solenoid pump with a two-way discharge control. The vibration mode FFT analysis result shows that a vibration between 199.7 Hz and 1532 Hz is generated in the first and second mode, 1,743 Hz in the second mode, and 2,082 Hz during the fourth vibration. A three-dimensional modeling is carried out for the proposed mechanism and then magneto static analysis and magnetic transient analysis are performed to investigate the lines of magnetic force and magnetic induction phenomena and to obtain a force generated from the piston in the pump. The generated maximum energy from the model is 3.057 MJ/m3 at the centre of coil and the pressure generated under the maximum energy condition is 39.5 MPa. This result could be implemented in the hydraulic system for small products used under a pressure less than 30 MPa. The result of natural frequency is as shown in the Fig.7.It has been observed that the strain and total deformation in the design standard were less than the allowances adopted in the processing and assembly of the products which implied that the implemented design secured the safety.

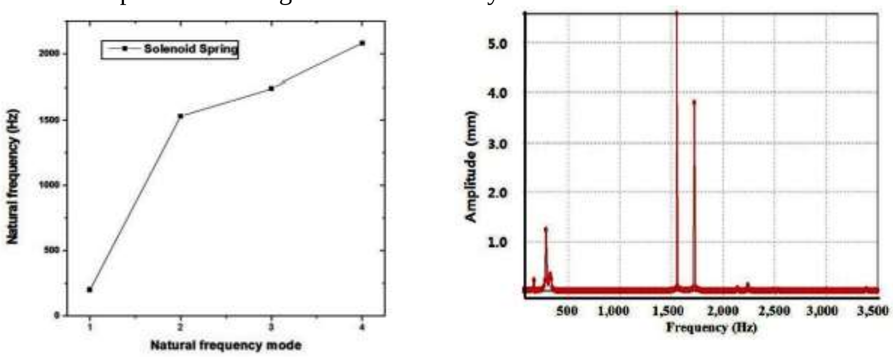

Fig.7 a) Natural Frequency b) FFT analysis

Sebastian Uzny [19] analyzed free vibrations and stability of hydraulic cylinder fixed elastically on both ends. The boundary value problem has been formulated on the basis of minimum potential energy (static problem) and on the basis of Hamilton’s principle (free vibration problem). Professional measuring apparatus and special stand for research into the slender systems have been used in experiment. Natural frequencies have been measured in dependence on the values of an external load. The results of numerical and experimental research stayed in good agreement in the case of the first basic frequency of vibrations as shown in the Fig.8.

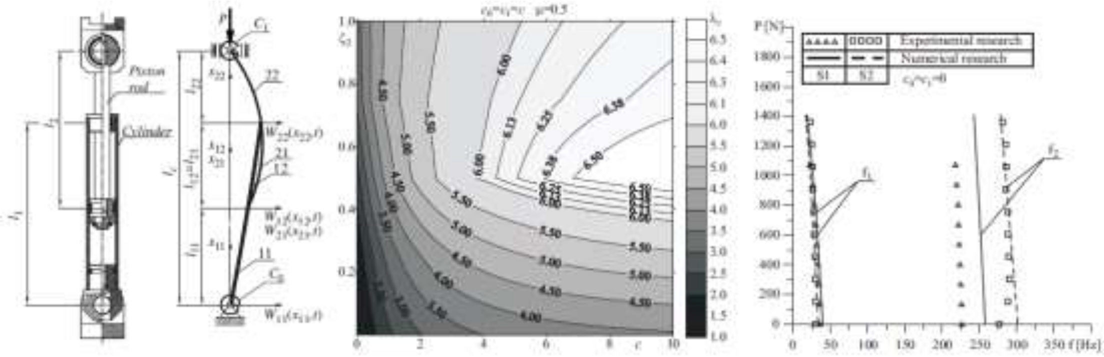

Fig.8 Physical and ideological model of the hydraulic cylinder, and results of numerical computations and experimental research

Pavankumar Shah et al. [20] carried out dynamic Analysis of Hydraulic Cylinder of JCB JS 130. The vibration of cylinder using simply supported beam concept under a moving point load was analyzed by using finite element analysis. Modal analysis was done on the basis of different mode. Total deformation under static loading condition has shown in the Fig.9. And the critical region of the cylinder was found by using finite element analysis.

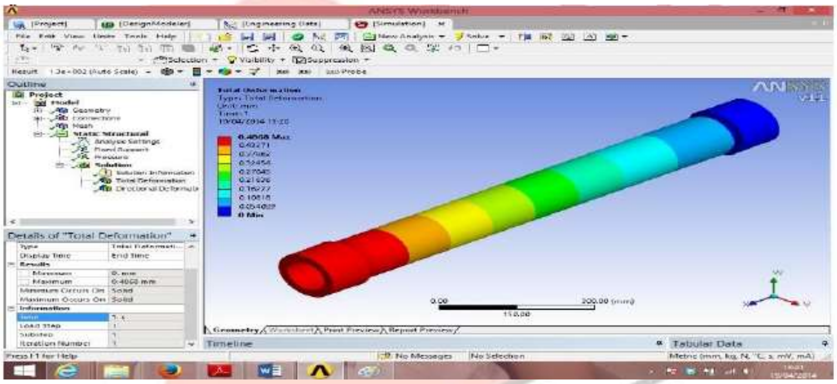

Fig.9. Total deformation of hydraulic cylinder

III. SUMMARY

After comprehensive study of existing literature on vibration analysis of a hydraulic cylinder, following observations have been made:

- The vibration analysis of the hydraulic cylinder is best way to predict the fatigue life of a cylinder and performance of a hydraulic system.
- The main cause of the vibration in hydraulic cylinder is stick-slip phenomenon between piston and cylinder which is also responsible for the failure of a sealing material and reduces the fatigue life as well the performance of the hydraulic system.
- Vibration analysis can be done by static, dynamic and transient way. The Mode Superposition Method of a transient dynamic analysis is one of the most important methods to predict mode shapes.
- Vibration analysis is possible by using finite different method ,by using mathematical model under variable loading application and different boundary conditions
- It was found during the comparison between the hydraulic cylinder element with the length controlled rod element that during starting and stopping of the movement the cylinder element softens the system.
- Imperfection angle is directly related with the load bearing capacity like; 5% of wear on the guide ring had reduced the cylinder load capacity by approximately 10%.

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