Dynamic behavior of steel core in the unwinding process

Vincent Caccese

ABSTRACT: The object of this study was development of guidelines for choosing the size of steel core for press operating parameters by investigating dynamic behavior during unwinding. The author tested steel cores containing various amounts of paper and different chuck pressures. Results correlated to an analytical model using the finite element method of analysis. Avoiding resonance was the choice criterion. A rotation of the core at or near its resonant frequency will almost certainly cause failure of the paper.

KEYWORDS: Chucks, cores, damping, dynamic tests, frequency, instructions, physical tests, resonance, steel, unwinding, velocity.

There is currently a trend in the paper industry toward increasing the width of paper rolls for press room operations. As the roll width increases, the problem of resonance of the roll becomes more prevalent. To reduce press room failures, it is therefore imperative to understand thoroughly the dynamics of the roll during unwinding. Resonance will typically result in excessive vibrations and will cause failures during a run. One investigator recently noted that problems in the press room are cyclic and that there are hundreds of thousands (or even possibly millions) of dollars expended each year due to press room failures *(1)*. The intent of this paper is to address specifically one type of press room phenomenon: excessive resonant vibration of the roll.

A recent study of the dynamic behavior of steel core in the unwinding process examined the dynamic properties of the core, the interaction between the core and the paper, and the influence of the chucks. This paper will describe the dynamic behavior of rolls during the unwinding process in general terms along with the details of the steel core study. There will be recommendations for choosing a steel core for a specific set of press operating parameters.

The object of this investigation was development of preliminary guidelines based on sound engineering principles for evaluating the runnability of the steel core in wider than normal presses. The underlying philosophy behind the guidelines is to avoid resonance. In other words, the rotational frequency of the roll should not approach the natural frequency of the roll. The speed at which resonance occurs is the critical speed. When the rotational speed of the roll approaches the critical speed, a disproportionately large amplitude of vibration will result. The effect of this phenomenon will typically be a tearing of the paper with concomitant inefficient press operations.

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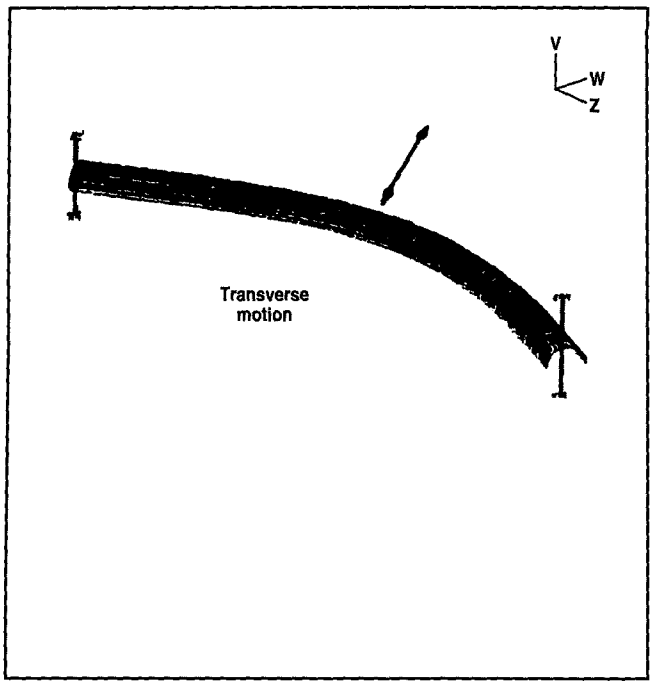
Resonance

Resonance of a vibrating system occurs when the frequency of the action which causes the vibration (hereafter called the forcing frequency) matches the natural frequency of the vibrating object. There have been multitudes of studies of the phenomenon of resonance over the past decades including a description for rotating machinery *(2, 3)*. Using that information which includes the effect of damping on a system, there are three influential factors on the amplitude of vibration for a rotating roll:

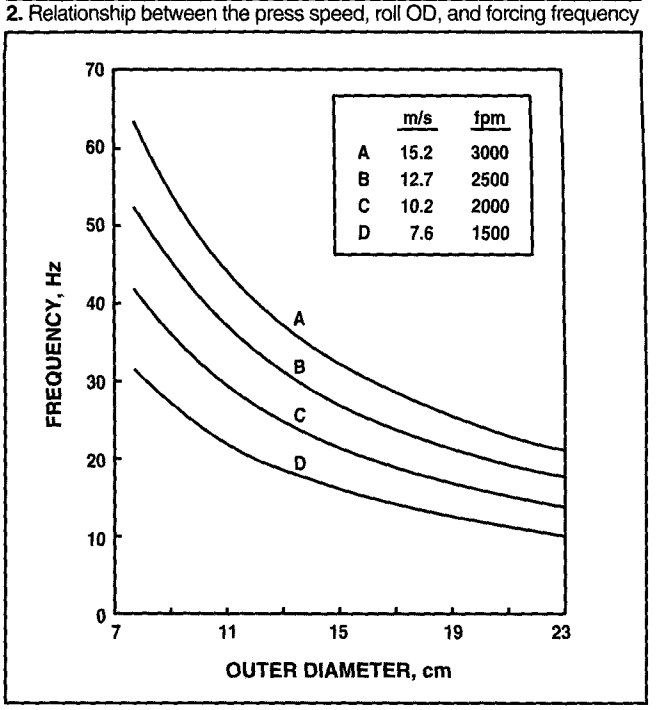
- The eccentricity of the roll
- The ratio of the forcing frequency, f, to the natural frequency, f_n
- The damping ratio.

As the forcing frequency approaches the natural frequency, the amplitude of vibration becomes quite high. **Table I** presents the relationship between the amplitude of vibration and the frequency ratio for a fixed damping ratio of 0.5%. The second column of the table quantifies the amount of eccentricity magnification due to the dynamic effects. When the forcing frequency is at 80% of the natural frequency, the magnification factor is about 1.8 com-

1. Lateral vibrational mode of the core



2. Relationship between the press speed, roll OD, and forcing frequency



pared to a factor of 100 when the system is at resonance. The out-of-plane vibration of the roll will be over 50 times greater. To avoid excessive vibrations, it is then necessary to ensure that there is no resonance.

Natural frequency of the roll

There is a transverse mode of vibration induced in the roll during unwinding as depicted in **Fig. 1**. It is like a beam which is vibrating transverse to the axis which passes through the center of its cross section. This vibration will be a combination of vertical and horizontal motions. When pulled back and released, the roll will vibrate back and forth a certain number of times in one second similar to the string of a musical instrument. This frequency of vibration is the natural frequency or resonant frequency. The units are cycles/s (Hz). The frequency depends on several factors:

- The mass and stiffness of the core
- The mass and stiffness of the paper
- The interaction between the core and the paper
- The type and condition of the chucks.

During unwinding, the natural frequency of the roll should be sufficiently higher than the forcing frequency. The fundamental or lowest natural frequency typically relates to the square root of the effective stiffness divided by the effective mass. Increasing the stiffness of the core relative to the mass provides a higher natural frequency.

I. The magnification of the deviation from straightness at varying frequency ratios using 0.5% damping ratio

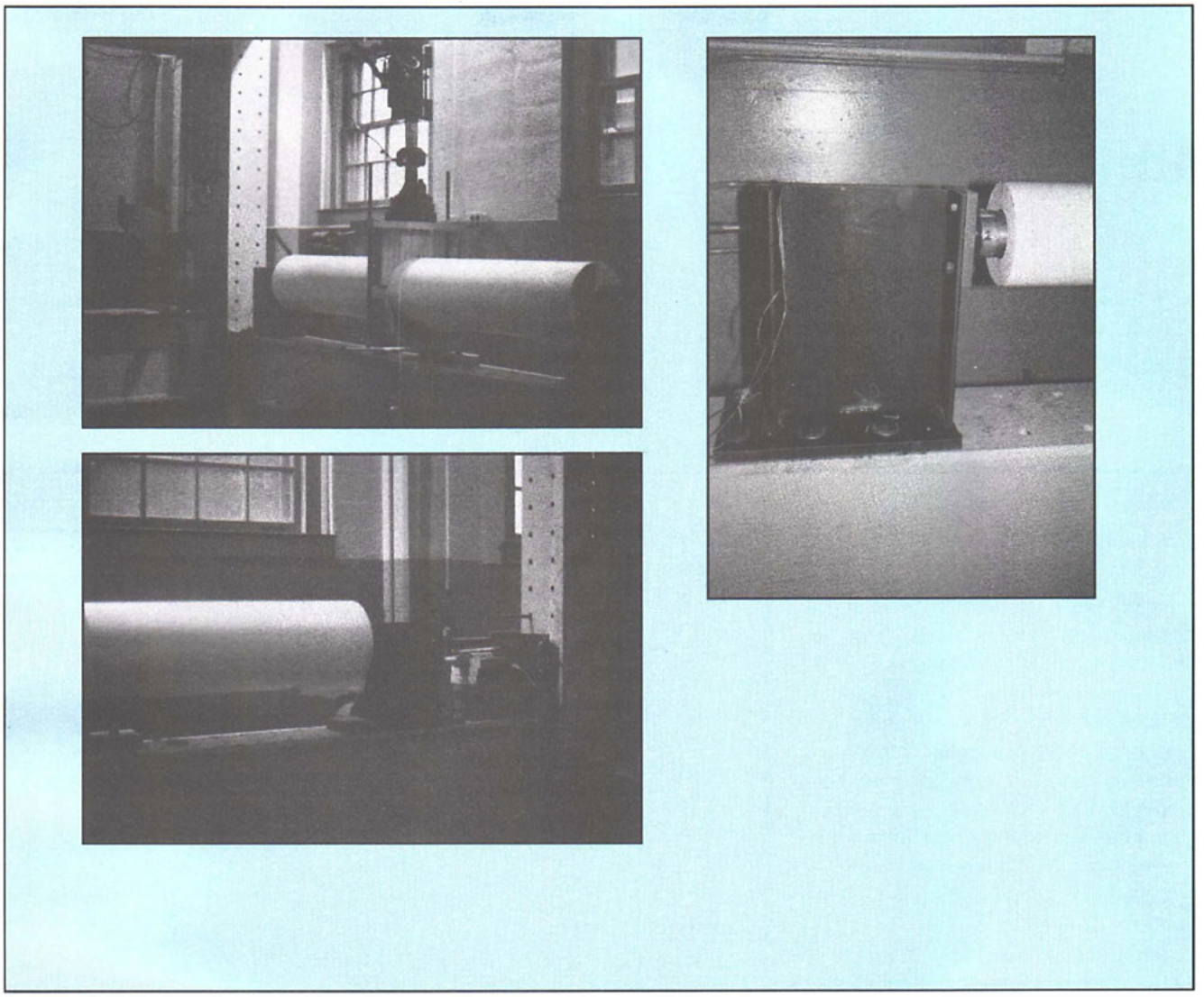
f/f_n	*Magnification factor*
1.00	100.0 (Resonance)
0.95	9.2
0.90	4.3
0.85	2.6
0.80	1.8
0.70	1.0
0.60	0.6

Core

The properties of the core which influence its dynamic behavior are the overall geometry (the width, OD, and wall thickness), the modulus of elasticity, the density of the core material, and the straightness of the core. The width will significantly influence the natural frequencies of the system. A reduction in width will generally increase the natural frequency. For example, a 7.62 cm (3 in.) standard core with pinned ends and a 304.8 cm (120 in.) width will have a natural frequency of 99 Hz. Note that decreasing the core width by half causes the natural frequency to increase by a factor of 4. An increase in core diameter will also serve to increase the natural frequency, since in this case the stiffness of the core increases at a faster rate than the mass of the core. The natural frequency increases accordingly. A slight change in wall thickness of the core does not have much effect on the natural frequency, since both the stiffness and the mass increase in this case. The effects of adding stiffness diminish with the additional mass.

Increasing the modulus of elasticity of the core material will also cause an increase in natural frequency. Steel has a modulus of elasticity which is much higher than most other structural materials such as aluminum or fiber. The modulus of elasticity for steel is a very consistent quantity with typi-

3. Photographs of Core A94 used in the vibration study



cal variations of less than 5%. The modulus of elasticity for most steels is typically 200 GPa (29,000,000 psi). In the case of steel cores, a change in natural frequency due to variance in the modulus of elasticity is not a significant influence.

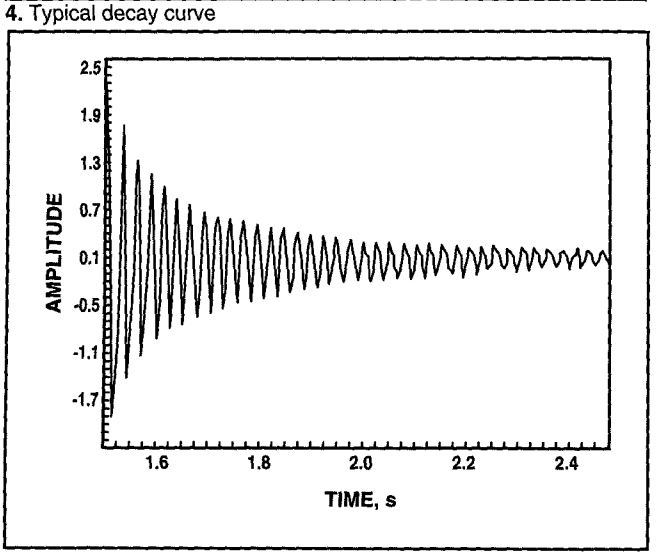
The initial deviation of the core from straightness will influence the vibration amplitude. Measurement of the divergence of the core from a perfectly straight line which spans the two ends of the core provides an indication of the deviation from straightness. For analytical purposes, one typically assumes there is a sinusoidal shape. Some deviation from straightness will occur in any core. Keeping the paper roll as straight as possible will help reduce the amplitude of vibration which relates directly to the eccentricity (deviation of the roll from straightness). In other words, if deviation from straightness doubles, then the vibration amplitude will also double. The deviation from straightness of the core will carry through to the paper during rewinding.

Paper

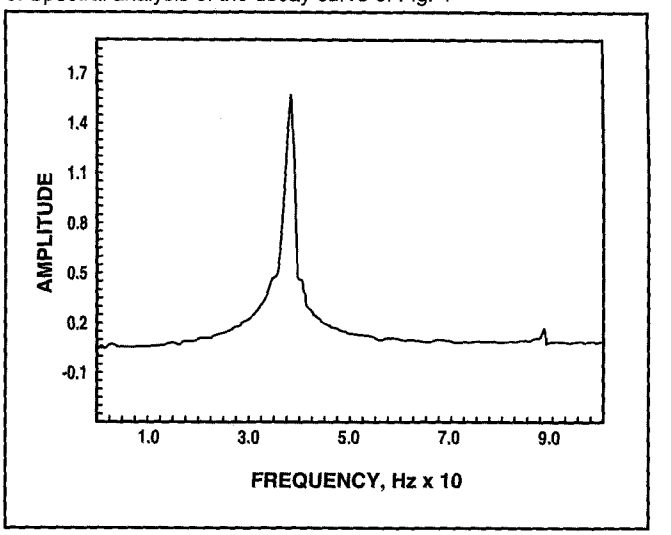
The paper will also have a significant influence on the dynamic behavior. It is much weaker than the steel core, and it has a much lower modulus of elasticity. Increase in paper stress due to vibration of the core will cause premature tearing of the paper. This is obviously most undesirable.

The tensile strength of the paper is an important consideration. Since the paper winds relatively tightly on the roll, it will contribute to the stiffness of the combined core and paper system. It also adds mass to the system. It will therefore influence the natural frequency of the roll. The important characteristics which quantify the influence of the paper are the density of the paper (as it winds on the roll) and the effective transverse bending modulus of the paper. Discovering the influence of the paper on the natural frequency of the roll is the key to an understanding of the roll dynamics.

4. Typical decay curve



5. Spectral analysis of the decay curve of Fig. 4



End conditions

Chucks provide the end supports for the roll. One investigator has offered a summary of various chuck types in use today *(4)*. He provides some of the influences of the chucks on runnability. Chucks will also affect dynamic behavior. For similar rolls, the difference in natural frequency between loose chucks and more rigid chucks can be more than a factor of two. In this case, increasing the rigidity of the chuck–bearing ends will increase the natural frequency of the roll. It is equally important to apply chuck pressure which is adequate but not excessive. These two conditions could provide the difference between a run where the paper fails prematurely and one where it does not. There is some advantage from improving the design of the chucks and the bearings.

Forcing frequency

The forcing frequency of a paper roll which is unwinding relates to the running speed of the press and the instantaneous OD of the roll. Removing paper from the roll decreases the roll diameter and conversely increases the rate at which the roll turns. The number of revolutions per second at which the roll turns is the forcing frequency. The forcing frequency increases at a faster rate with additional paper removal from the roll. **Figure 2** graphically depicts the change in forcing frequency as the OD of the roll changes for various press speeds. Notice in Fig. 2 that the system is moving from the right- to the left-hand side of the figure along one of the solid curves which depend on press speed as the roll turns. The figure shows how the forcing frequency dramatically increases with paper removal and a reduction in the net OD.

Quantitative study of roll vibration

This study examined the dynamic behavior of the steel core using vibration tests and finite element computer analysis *(5)*. The intent of this study was an estimation of the natural frequencies for rolls of varying widths and core cross sectional dimensions. Since it is very costly and nearly impossible to perform vibration tests on every condition under which a roll will operate, the philosophy of the study was an initial verification of the working of the computer finite element model. Following this, there would be variation of the parameters using the finite element analysis.

Test program

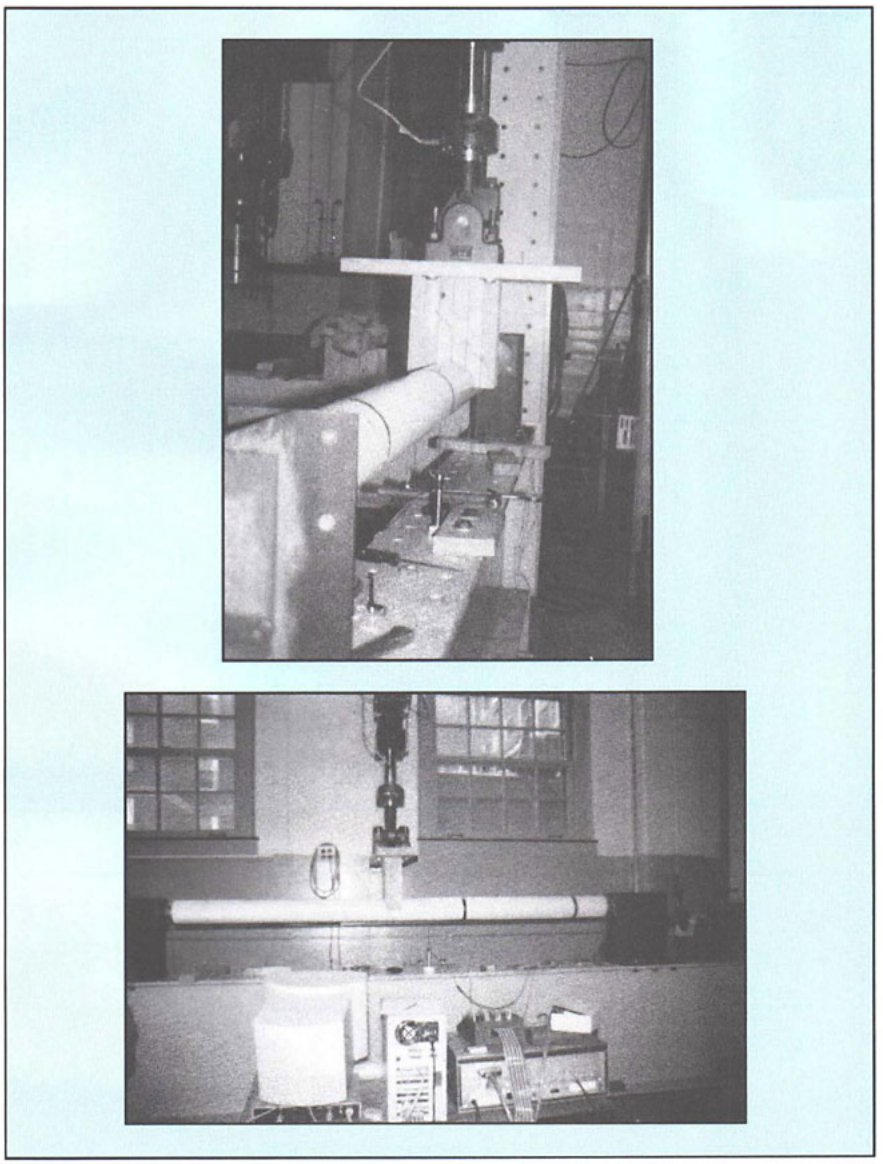
The purpose of the vibration study was quantification of the interaction between the paper and the core. There was also an investigation of the influence of the boundary conditions on the dynamic behavior. To achieve this goal, the study plan included measurement of the effective transverse bending stiffness, the natural frequency of vibration, and the damping characteristics. There were tests under varying end conditions and with varying amounts of paper on the roll.

The cores were standard types consisting of 7.6-cm (3 in.) steel measuring 240 cm (94.5 in.) and 214 cm (84.3 in.) in width. Their designation hereafter is Core A94 and Core B84, respectively. At the

II. Force and equivalent pressure on the chucks

Chuck force		Chuck pressure	
kN	*lb*	*kPa*	*psi*
2.2	500	356	51.7
4.5	1000	712	103.3
8.9	2000	1424	206.7
13.4	3000	2136	310.0

6. Photographs of the load–deflection test arrangement



start of the investigation, each core contained approximately 12.7 cm (5 in.) radially of a white coated paper. **Figure 3** offers views of Core A94 mounted in the test arrangement.

There were two basic tests performed on the paper roll: a dynamic free vibration test and a static load–displacement test. The free vibration test is a reliable method which provides the natural frequency and damping ratio of a mechanical system. One performs this test by exciting the system using an initial velocity and recording the time–history of the decay response. This is a decay curve. In this experiment, striking the roll with a rubber mallet excited the roll. A computer data acquisition system recorded the time–history using a direct current displacement transducer (DCDT) to track the displacement response.

Figure 4 presents a sample decay curve for a 7.6-cm (3 in.) core at 23.2 cm (9.1 in.) OD. Notice the decrease in amplitude with time. This is due to damping and is typical for this type of test. From the decay data, one determines the natural frequency using the FFT (spectral analysis) algorithm. **Figure 5** shows the associated spectral analysis performed on the data set from Fig. 4. Note that there is a single dominant peak at a frequency corresponding to the fundamental (natural) frequency of the roll.

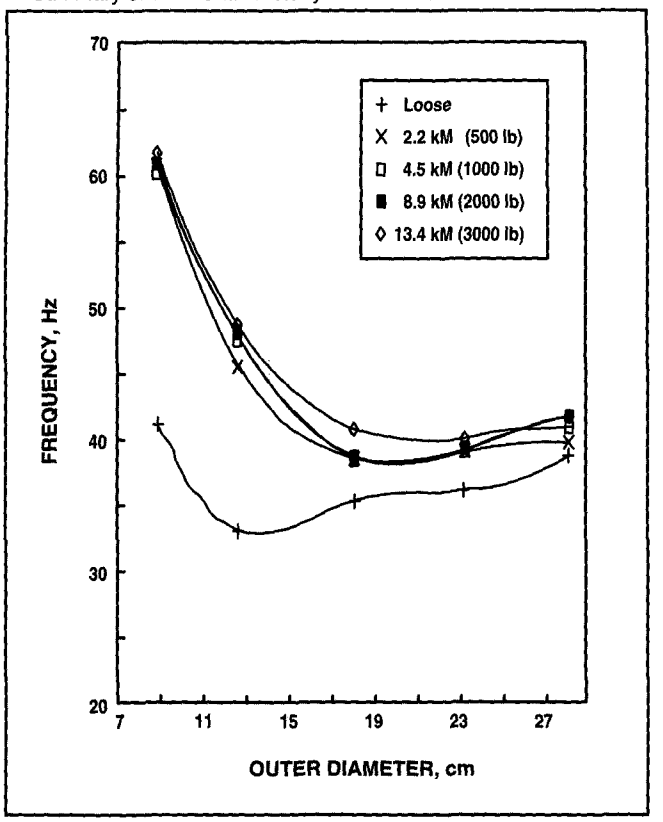
The load–displacement tests involved pushing on the roll at its center with a computer controlled hydraulic actuator which can apply a known value of force. Using the DCDT allows measurement of the resulting displacement. A timber load head shaped to the OD of the roll as the photographs of **Fig. 6** indicate applies the force to the OD of the roll. There was a different load head for each roll diameter undergoing testing. A statistical analysis of the data determined the stiffness of the roll in terms of force per unit measure of deflection.

The testing program measured the vibration properties and stiffness of the rolls with varying amounts of paper on the roll and pressure on the chucks. Mounting of the roll was between a set of chucks which had a tapered cross section. There were tests performed with different amounts of pressure on the chucks. Initially the chucks were relatively loose. After measuring the natural frequency of the roll, the chucks received additional pressure. Again there was measurement of the frequency. This process repeated for different chuck pressures. **Table II** shows the relation of force on the chuck to uniform pressure distributed over the OD of the core. After completion of this set of tests, there was approximately 2.5 cm (1 in.) radially of paper removed from the roll. The process repeated again until no paper remained on the roll. There were also tests of the bare core.

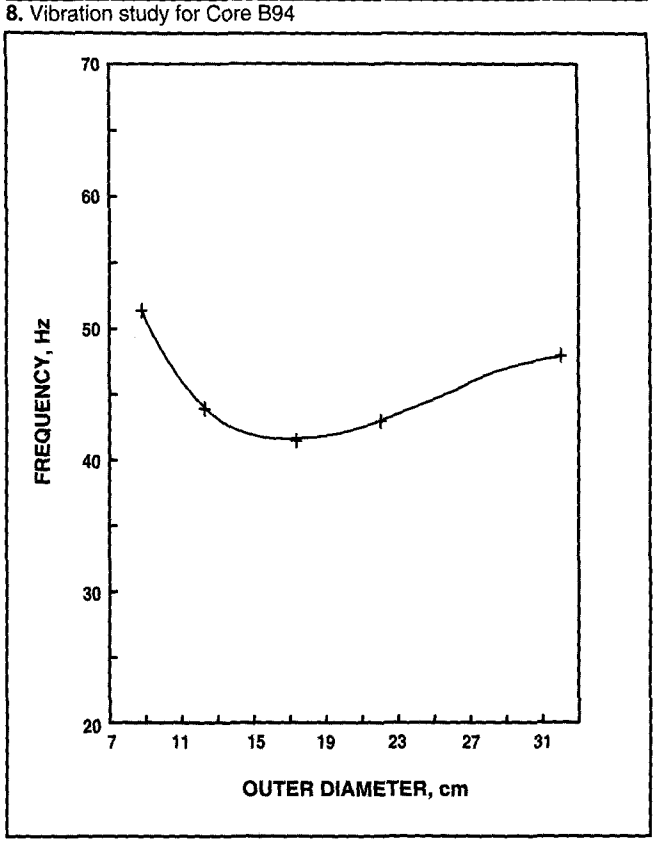
Vibration study results

Figure 7 summarizes the results of the vibration testing showing changes in natural frequency for various values of OD with Core A94. Each curve represents the results at a particular level of applied chuck pressure. To expedite the testing process, Core B84 did not undergo varying chuck pressure. The end condition for this roll was near the loose state. **Figure 8**

7. Summary of the vibration study for Core A94



8. Vibration study for Core B94



shows the vibration study for Core B84. Figure 7 indicates for Core A94 that there is a substantial difference in behavior between loose and pressurized chucks. For the bare core, the natural frequency increased from 41.3 Hz to 61.0 Hz. Comparing the cases where chuck pressures were applied to each other, there was not much difference in natural frequency. From this, it is possible to conclude that there should be a minimum amount of chuck pressure applied for efficient operation. After this, little benefit will occur upon application of additional pressure. In addition, it is possible that application of too much pressure may in some instances be detrimental, since this pressure acts as an axial load on the core. There was no such detrimental effect observed under the pressures of this study. In summary, a minimum amount of pressure is necessary to gain some benefit from the stiffness of the chucks.

III. Stiffness at various diameters

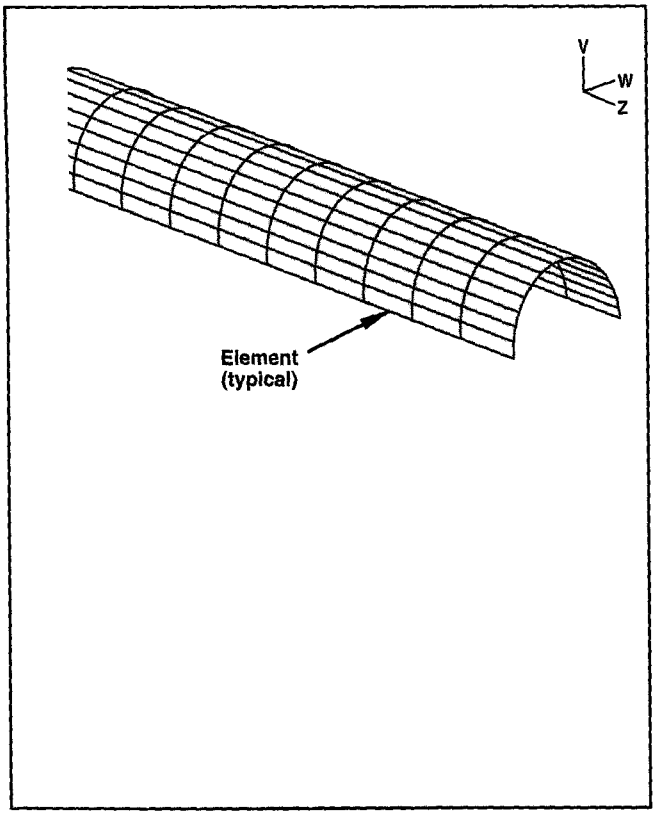
Core A94				Core B94			
Outside diameter		Stiffness		Outside diameter		Stiffness	
cm	in.	kN/m	lb/in.	cm	in.	kN/m	lb/in.
33.7	13.3	9,759	55,767	32.1	12.6	11,125	63,571
28.1	11.1	5,683	32,475	27.5	10.8	6,634	37,907
23.2	9.1	3,321	18,975	22.1	8.7	3,844	21,966
18.1	7.1	1,800	10,278	18.0	7.1	2,268	12,961
12.7	5.0	1,297	7,410	12.3	4.8	1,422	8,128
8.9	3.5	1,142	6,524	8.8	3.5	1,257	7,185

Load–displacement test results

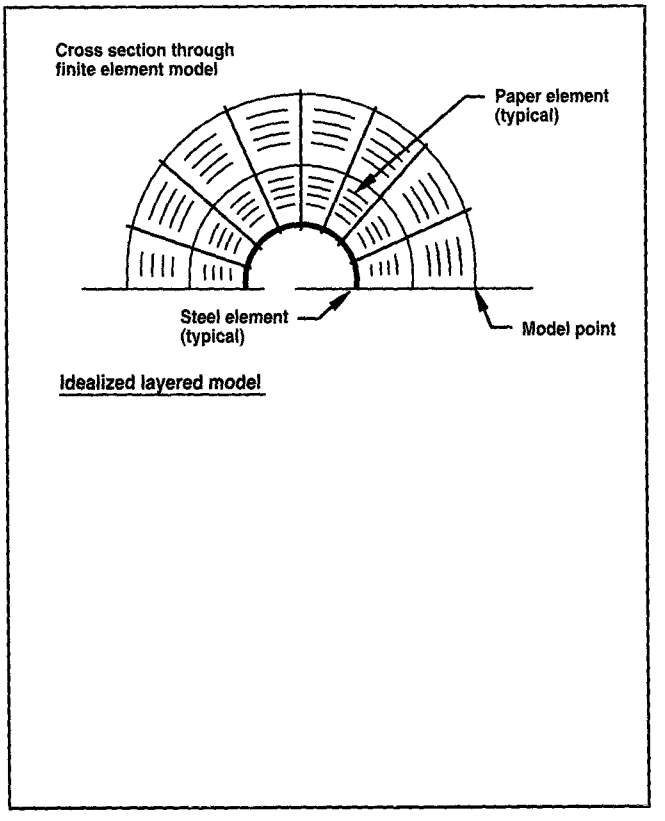
Table III presents the results of the load–displacement tests for both rolls. In both cases, a substantial increase in stiffness comes from the paper as the OD of the roll increases. Core A94 with no paper on it had a stiffness of 1.142 kN/m. With 12.4 cm (4.9 in.) of paper added radially, the stiffness increased by a factor of 8.5 to 9.759 kN/m. There was a similar occurrence in Core B84. This indicates that the paper contributes substantially to the stiffness of the roll. As the OD of the roll increases, the influence of the core on the system decreases.

The results of this test also allowed computation of the effective transverse modulus and the as–wound density of the paper. At the different diameters studied, the effective modulus had an average value of 3.1 GPa (451,600 psi) for Core A94 and 3.5 GPa (513,700 psi) for Core B84. The average as–wound density was 12.2 kN/m^3 (78 lb/ft^3) for Core A94 and 13.2 kN/m^3 (84.3 lb/ft^3) for Core B84.

9. Finite element model of the steel core without paper



10. Finite element model of the steel core with paper



Steel core development criteria

Use of a finite element analysis approach allowed development of the criteria necessary to determine the choice guidelines for the steel core. Following are some details of the finite element model and its correlation to actual rolls. There is also a summary of the results of a parametric study varying the roll width and core type.

Finite element analysis

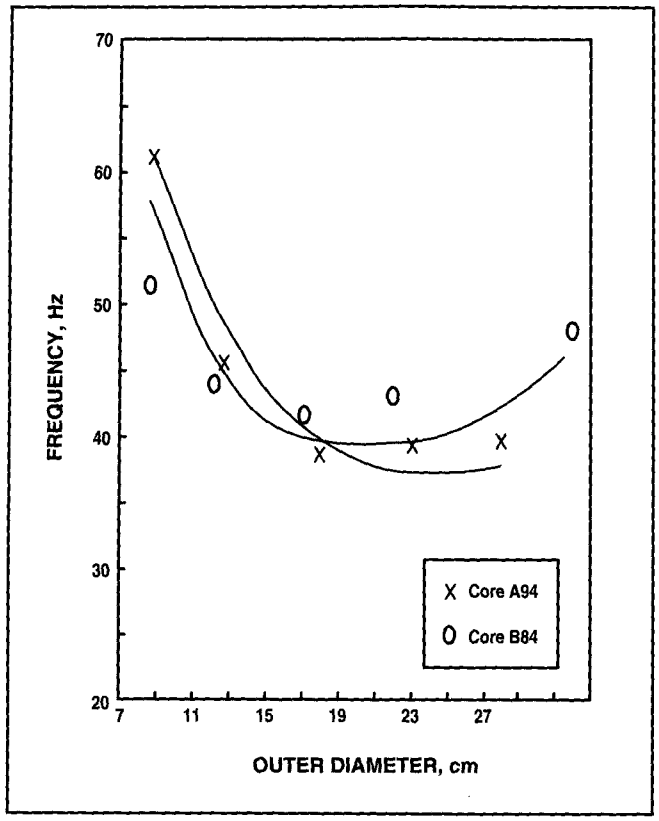
The finite element method of analysis is a proven numerical technique using segmentation of a body into small pieces or elements. One assigns properties to the elements that match the characteristics of the material which they represent. Then there is a numerical analysis using a computer to allow calculation of a quantity such as the natural frequency. Simply changing the input to the model allows comparison of different rolls. **Figure 9** shows a view of the model of a steel core with no paper on it. This particular model has only one layer of steel. Note that the system contains a series of elements which have the properties of steel. Their thickness would be that of the steel core. The elements connect at common points called nodal points. The boundary conditions of this model are the nodal restraints at the ends of the core. To include the effects of the paper in this system, the model contains another layer or two. **Figure 10** shows a core with two additional layers of paper elements. These elements would have the properties of the paper such as the effective bending modulus and the as-wound paper density. It is possible to model different roll OD values by selection of the desired thicknesses for the paper layers.

The properties of the paper, the properties of the steel core, and the characteristics of the chucks were data for the finite element model. **Figure 11** gives the comparison between the physical test and the computer model for Core A94 and Core B84. This figure shows the relationship between the OD of the roll and the natural frequency of the roll. With removal of the paper from the roll, the curve proceeds from the right side to the left side of the figure. In both cases, the natural frequency first decreases with initial paper removal and then increases as it approaches the natural frequency of the bare steel core. There is a close correlation between natural frequency of the actual roll and the finite element analysis. This gives confidence in the finite element model.

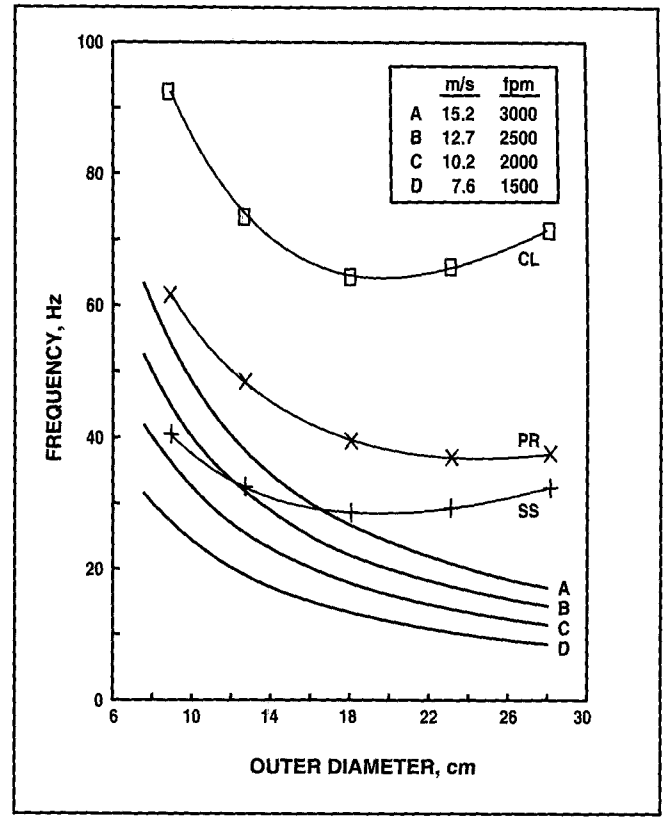
Effect of end conditions

Having examined the interaction between steel and paper, the next step was analysis of the influence of the end restraint. **Figure 12** presents the results of the 240-cm wide (94.5 in.) roll analyzed under varying end restraints. The two ideal cases of clamped (CL) and simply-supported (SS) are the upper and lower boundaries. The partially restrained (PR) case lies between these two cases. Note that the PR case approaches the SS case as

11. Comparison of the finite element analysis to the vibration study



12. Comparing the influence of the end conditions using CL, PR, and SS for a 240-cm-wide (94.5 in.) roll



the OD increases. Figure 7 shows this behavior experimentally. Figure 12 also shows the forcing frequency traces (run speed curves) for press speeds of 15.2, 12.7, 10.2, and 7.6 m/s (3000, 2500, 2000, and 1500 ft/min). Resonance occurs when the natural frequency curve crosses the run speed curve. One should avoid this state.

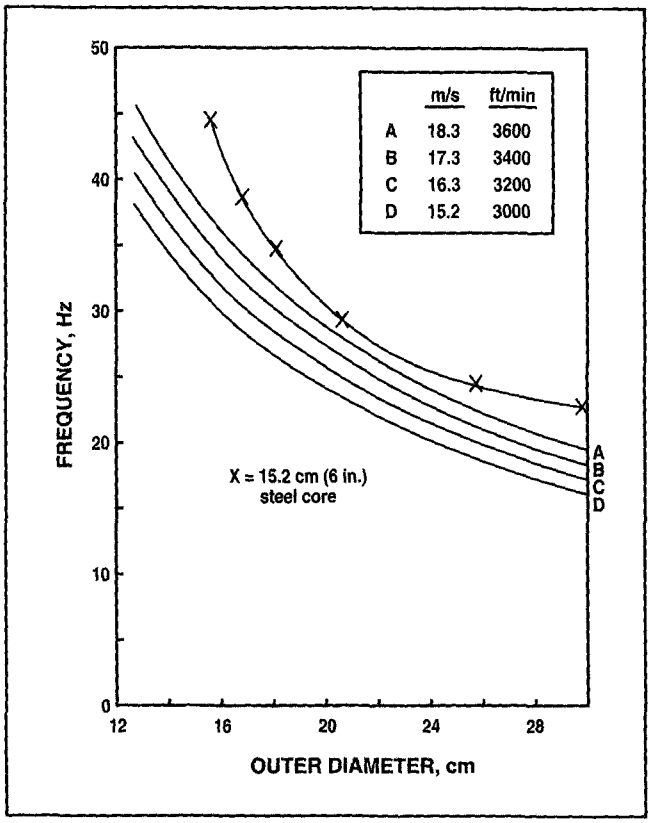
15.2-cm steel core behavior

Figure 13 presents the general behavior of 15.2-cm (6 in.) steel core for a 381-cm-wide (150 in.) roll. In this case, the forcing frequency at which the core is devoid of paper is much less than in the case of 7.6-cm (3 in.) core, since the OD has a larger value and the forcing frequency increases as the OD decreases. For this reason, this size core is more applicable to wider presses. It is also preferable because the 15.2-cm core has a greater stiffness to mass ratio which results in a higher natural frequency. In Fig. 13, the press speeds reported on the graph increased to 18.3, 17.3, 16.3, and 15.2 m/s (3600, 3400, 3200, and 3000 ft/min). With paper removal from the roll with a 15.2-cm (6 in.) core, the behavior is somewhat different from that of the 7.6-cm (3 in.) core. For the 7.6-cm (3 in.) core, as shown in Fig. 12, the natural frequency of the roll will approach the critical forcing frequency curve when the roll becomes devoid of paper. For the 15.2-cm core, the natural frequency curve will touch the forcing frequency curve at a point where there will be a substantial amount of paper remaining on the roll. One must therefore keep this size core further away from resonance. In the choice criteria of the next section, there is a conservative approach by reducing the frequency ratio limit from 0.80 for 7.6-cm (3 in.) cores to 0.75 for 15.2-cm (6 in.) cores.

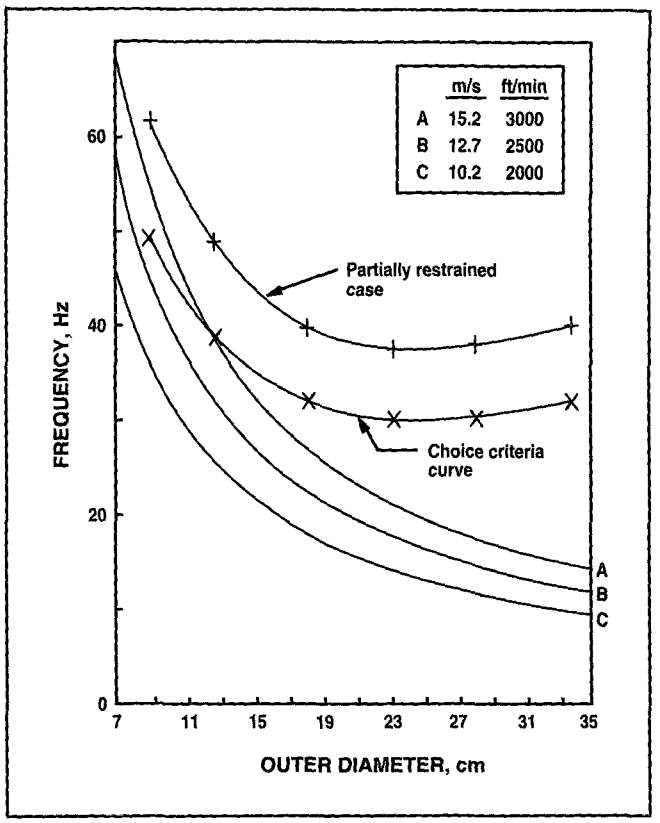
Core size criteria

The appropriate choice criterion for paper rolls is one avoiding resonance. Referring to Table I, one can note again that at resonance the amplitude magnifier is 100, compared to a value of less than 2, when the driving frequency is 80% of the natural frequency. To ensure a reduction in vibration amplitude of this extent, it is necessary to multiply the frequencies in the partially restrained case by 0.80 for the case of 7.6-cm (3 in.) core and 0.75 for 15.2-cm (6 in.) core. These curves where the natural frequency curve is modified by the 0.8 and 0.75 multipliers are the choice criteria curves. **Figure 14** plots the natural frequency curve and the choice criterion curve for the 7.6-cm-diameter (3 in.) core and 240-cm-wide (94.5 in.) roll described above along with the forcing frequency curves at run speeds of 15.2, 12.7, 10.2, and 7.6 m/s (3000, 2500, 2000, 1500 ft/min). Note that, in this figure, the bare core occurs where the left-hand side of the natural frequency and choice criterion curves terminate.

13. Natural frequency vs. OD of a 381-cm-wide (150 in.) roll on a 15.2-cm (6 in.) steel core



14. Example choice criteria for 7.6-cm (3 in.) steel core



The decision criterion is such that for a given run speed and core length the choice criterion curve should not meet the run speed curve. In other words, for the roll presented in Fig. 14, it should be possible to use fully the paper at press speeds below 13.5 m/s (2650 ft/min).

Comparison with press runs

It is now possible to compare the choice criteria to actual press runs. The first two case studies use 274-cm-wide (108 in.) rolls examined by another investigator *(6)*. These rolls experienced vibration problems and paper rupture. **Figure 15** shows the first case which ran at a press speed of 12.4 m/s (2450 ft/min). Notice that in time the system is moving from the right- to the left-hand side of the page. The roll forcing frequency moves along the curve representing operation at 12.4 m/s in the direction of the arrows indicated on the figure. Notice further that the forcing frequency curves cross the choice criterion curve at an OD of approximately 14.2 cm (5.6 in.). This is the point where vibrations should commence. The press run stopped shortly after this occurrence, because the paper broke. **Figure 16** shows a similar occurrence for another case. The choice criterion curve adequately predicts again the onset of vibration problems.

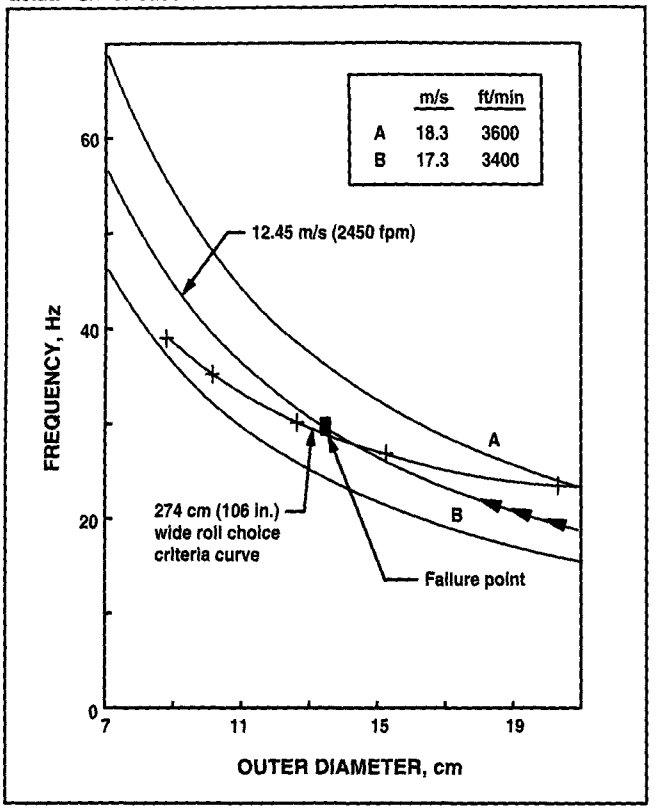
Steel core selection

The next step was implementation of the choice criteria for the 7.6-cm (3 in.) steel core. The investigation analyzed roll widths from 218 cm to 305 cm (86 in. to 120 in.) in increments of 5.1 cm (2 in.) under PR end conditions. As an example, for the 274-cm-wide (108 in.) roll, it is possible to achieve full usage of the paper at a press speed of about 10.7 m/s (2100 ft/min) without detrimental vibration. The collection of curves allowed development of recommendations. **Table IV** summarizes these recommendations. For a given press speed, this table gives a recommended value for the core width using the choice criteria described above. There was a similarity for 15.2-cm (6 in.) core except for a limitation of the frequency ratio to 0.75. Table IV also shows these results.

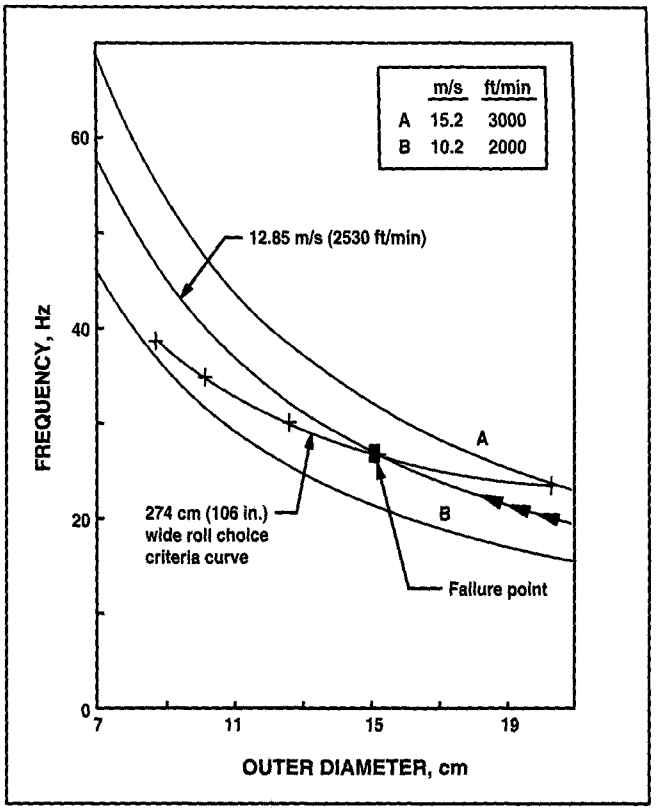
Future studies

Study of the behavior of steel core for use in the paper and related industries should be a continuing process. This paper therefore offers some recommendations for future studies. The interaction between the paper and the core used two rolls of paper. The size of this data base should increase to include paper of various types and paper rolls from different manufacturers. Documentation of successful and problematic runs of steel core should continue. It is during the actual operation that one can obtain the most information. The documentation should include at least the following information:

15. Comparison of the choice criteria for a 274-cm (108 in.) wide roll to actual run for case 1



16. Comparison of the choice criteria for a 274-cm (108 in.) wide roll to actual run for case 2



- The paper type and approximate density as wound on the roll (It is possible to approximate this if one knows the paper volume and the gross weight of the roll.)
- The chuck type and amount of pressure
- The roll width and core cross section dimensions
- The running speed
- The amount of paper on the core at the initiation of the problem, if vibration occurs
- The amount of paper remaining and the gross weight of the roll, if paper stays on the core.

There should also be vibration monitoring of paper rolls during the time of the run. It is possible to monitor the change in vibration amplitude of the roll in actual operating conditions. In doing so, one can learn much about interaction between paper and core as well as the influence of the end conditions. There should also be an attempt to examine more deeply the in-plane stress induced into the paper during vibration and its relationship to the amplitude of vibration. It is this change in stress that causes tearing of the paper.

IV. Recommended maximum roll width at various press speeds for 7.6 cm (3 in.) and 15.2 cm (6 in.) steel cores

Running speed		*7.6 cm Core*		*15.2 cm Core*	
m/s	*ft/min*	*cm*	*in.*	*cm*	*in.*
15.2	3000	224	88	368	145
14.2	2800	231	91	381	150
13.2	2600	241	95	399	157
12.2	2400	254	100	-	-
11.2	2200	267	105	-	-
10.2	2000	279	110	-	-

Summary and conclusions

The key to proper use of cores in the unwinding process is to avoid relatively large amplitudes of vibration at or near resonance which will cause tearing of the paper and other detrimental effects. One can accomplish this through careful choice of the core. A resonant vibration of the roll will cause the amplitude of vibration to increase at an unacceptable rate. For this reason, the criteria summarized in this paper has emphasized the need to avoid resonance, since one should avoid the critical speed of the roll. In addition to avoiding resonance, it is necessary to have reasonably straight rolls, since the amplitude of vibration is di-

rectly proportional to the deviation from straightness of the roll.

The end conditions for roll mounting using the chucks and bearings also have an important role in the vibration of the core and paper system. Theoretically speaking, a staunch end condition which allows little transverse rotation at the core ends will cause a substantial increase in the natural frequency compared to the case of a loosely mounted roll. Practically speaking, actual end conditions will lie somewhere between these two cases. Improvements are possible by employing chucks and bearings which allow less transverse rotation at the ends of the core. Wider rolls are possible and less vibration problems will occur simply by using improved end conditions.

Several conclusions arise at this point regarding the behavior of steel core when used in the unwinding process. Avoidance of vibration problems in unwinding at run time is possible by proper choice of core for a given press run speed. The paper presents recommendations for choosing 7.6-cm (3 in.) and 15.2-cm (6 in.) steel core at various press speeds. Following these recommendations should help to minimize vibration of the roll during unwinding and lead to fewer failures at run time.

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