MECH4860 Final Design Report

Flexographic Printing Redesign

Sponsoring Company: Winpak

Project Advisor: Edward Hohenberg, P. Eng.

December 2, 2013

Prepared by:

Team 16

Justin Phill ______________________

Aron Houssin ______________________

Jordan Moncek ______________________

Cher Yeng Chan ______________________

December 2, 2013

Dr. Paul Labossiere, P. Eng
Professor
University of Manitoba
66 Chancellors Circle
Winnipeg, Manitoba R3T 2N2

Chris M. Parker, P. Eng.
Plant Manager
Winpak Limited

Winnipeg, Manitoba

Dear Dr. Labossiere and Mr. Parker,

Please find enclosed our Final Design Report for our Flexographic Printing Redesign project for Winpak Limited.

Winpak has experienced issues with a phenomenon known as bounce in their printing process. This report was written to explain possible causes of bounce, and to suggest solutions to the possible causes.

The report looks at bounce caused from resonant frequencies of the printing rollers, bounce caused from rotational imbalance of the printing rollers. Suggestions on how to reduce bounce from these two problems by improving the doctor blade design and choice of stickyback tape are offered.

If you have any questions, please do not hesitate to contact us.

Regards,

Justin Phill
Team Manager
Team 16

Enclosures: 1

Table of Contents

List of Figures

List of Tables

Glossary of Terms

Banding	The appearance of inconsistencies in the final print, typically in the form of periodic rows transverse to the print direction.
Bounce	A phenomenon which may occur in the flexographic printing process whereby periodic inconsistent contact pressure occurs during operation.
Flexography	A printing process which employs a flexible printing plate.
Lamella	In terms of the doctor blade, a thin ‘step down’ edge that keep the transfer of ink consistent throughout the production run.

Executive Summary

Winpak Limited is an international company which manufactures and distributes high quality packaging material and related packaging machines. Food, beverage, and health care packaging are some of many products Winpak has to offer. The design for the packaging is created through a flexographic printing process.

The machines used in the flexographic printing process are capable of producing packaging up to a rate of 500 metres per minute. The machines are currently running at 100 metres per minute or less due to a phenomenon called "bounce." Bounce is recognized by print variability, specifically in the formation of horizontal bands where the ink transfer is noticeably diminished or increased. The phenomenon does not appear at low printing speeds, but begins to occur when print speeds approach 100 metres per minute. Bounce is currently limiting the amount of packaging Winpak can produce.

The team was tasked with the goal of finding what could be causing bounce in the printing process and to recommend possible solutions to the problem. Resonance and rotational imbalance of the rollers, the doctor blade used to remove excess ink from the printing material, and the stickyback tape used to hold the print template to the roller were all areas the team investigated.

A modal analysis of one of the print cylinders was created in ANSYS. The first vibration mode occurs within the operating speed of the printing press. This means bounce could occur at a print speed of 270 meters per minute. However, the finite element model does not take into account environmental effects, or vibrations occurring in other components of the printing press, which can change the speed which bounce would occur at. This mode shape would cause the material at either end of the print cylinder to print more faint than the material in the middle.

The recommended course of action is to install a new doctor blade and try a different brand of stickyback to increase the amount of damping on the print rollers. Increasing the amount of damping should reduce the amount of vibration, and bounce as well. A doctor blade design is included, as well as a recommendation to look at the MDC StableFlex doctor blade made by Daetwyler for an off the shelf solution. Winpak purchases stickyback from 3M, and the new recommendation is to try the 17 or 18 series stickyback tape from the same manufacturer.

1 Introduction

Winpak Ltd. is a Winnipeg-based company which manufactures and distributes high quality packaging materials and related packaging machines. The packaging products produced by Winpak are primarily used for the protection of foods, beverages and health care products. Winpak currently employs a flexographic printing process for the printing of many of packages, which involves the transfer of ink to the packaging material through a series of rotating drums and specialized materials (Figure 1).

Figure 1: Example of one of Winpak's flexographic printing presses

The rate at which packaging materials are printed is variable; ideally, production rates should be as high as possible in order to maximize profitability. With that Winpak's machinery degrading over time, having been purchased in the 1990s, the company is encountering a problem known as “bounce”. Bounce is a phenomenon which is recognized by print variability, specifically in the formation of horizontal bands where the ink transfer is noticeably diminished or increased. Bounce is encountered when print speeds are increased to approximately 100 metres per minute, which has caused Winpak to reduce printing speeds to less than 100 metres per minute – Winpak desires a printing speed of 500 metres per minute, which is the maximum speed of the printing press [1].

This team has been tasked with the investigation of Winpak’s bounce problem in order to offer insight into its root cause. The team will investigate several key components of the flexographic printing press, using research and analysis techniques in order to pinpoint the strongest contributing factors to the bounce problem in Winpak’s flexographic printing process. Upon identifying the root cause(s) of bounce in Winpak’s machines, the team will then offer recommendations and design insight to Winpak. The intent of this project is to offer recommendations which are feasible to implement with Winpak’s existing machinery. Only modifications to existing equipment are possible due to the high capital cost involved in the purchase of a flexographic printing press. This project is intended to address the specific needs stated by Winpak, which is to help Winpak understand the root cause of bounce and how to eliminate it.

1.1 Client Needs

The team began generating client needs with the project definition report. These needs were a basic start to understanding the parameters laid out for the upcoming concept generation part of the project. These needs were based solely on the project description provided. A further understanding of the client's needs was developed upon the completion of a site visit of Winpak's facility. After the site tour and meeting, the team was better able to understand which deliverables were expected from the client. The team then reevaluated the needs of the client and began to rank the needs in order of importance based on what was learned from the meeting. The results of the needs generated and their relative importance are shown in Table I.

TABLE I:
CLIENT NEEDS AND THEIR RELATIVE IMPORTANCE [1]

#	Need	Ranking Number (5=Most Important, 1=Least Important)
1	Management of frequencies and harmonics produced by flexographic printer	5
2	Product allows for consistent contact between rollers	4
3	Low cost (ie: small payback period)	1
4	Easy maintenance	2
5	Easy to use	2
6	Product follows codes and regulation of food packaging facility	5
7	Allows for adjustment	4
8	Product can be applied to Winpak's current flexographic printers	5
9	Product allows for constant production runtime	3
10	Safe to operate	5

1.2 Technical Specifications

The team created a list of applicable metrics from the client's specified needs in order to create a set of technical specifications for concept generation. The metrics that were used and their relationship to the client's needs are presented in Table II.

TABLE II:
METRICS AND THEIR RELATIONSHIP TO CLIENT'S NEEDS [1]

#	Relates to need	Metric	Units	Importance
1	1,2	Precision monitoring of vibration data	Hz	5
2	1, 2	Printing press rate	m/min	5
3	3	Manufacturing cost of product	$	1
4	3, 4, 9	Time to resolve any maintenance issue	Min	2
5	3, 5	Training time	Days	2
6	3, 5	Assembly time	Min	1
7	6	Levels of possible food contaminants	PPM	5
8	2, 7	Product adjustability	Hz	4
9	8	Product fit on existing hardware	Boolean	5
10	3, 5, 10	Total mass	Kg	3
11	10	Time between safety issues	Days	5
12	11	Product lifespan	Months	1

The metrics were then evaluated at marginal and ideal values to yield target specifications. The values for the marginal and ideal data were obtained from two different sources. The first source was obtained from available product research of designs that were already in industry which were marketed to solve bounce-related flexographic printer problems. The second source is from the meeting with the client and tour of the Winpak facility as they had expressed certain criteria that needed to be implemented. An example criterion is that it would be imperative to have a product that followed all codes and regulations with regards to the food industry, since Winpak produces products which are used for food packaging [1]. Table III illustrates the team's metrics, as well as their formulated ideal and marginal values.

TABLE III:
METRICS AND THEIR ASSOCIATED MARGINAL AND IDEAL VALUES [1]

#	Relates to need	Metric	Units	Importance	Marginal Value	Ideal Value
1	1,2	Precision monitoring of vibration data	Hz	5	0-200, >3 frequency sample rates	0-400, >5 frequency sample rates
2	1, 2	Printing press rate	m/min	5	200-500*	500*
3	3	Manufacturing cost of product	$	1	<5000	<500
4	3, 4, 9	Time to resolve any maintenance issue	Min	2	<30	≤5
5	3, 5	Training time	Days	2	1-3	<1
6	3, 5	Assembly time	Min	1	<120	<20
7	6	Levels of possible food Contaminants	PPM	5	≈0	0
8	2, 7	Product adjustability	Hz	4	Accuracy within one unit place	Accuracy within one decimal point
9	8	Product fit on existing hardware	Boolean	5	True	True
10	3, 5, 10	Total mass	Kg	3	<100	<10
11	10	Time between safety issues	Days	5	>365	∞
12	11	Product lifespan	Months	1	>12	>36

The team determined that the most important target specifications, as related to the client’s needs, include:

1. Adjustability - frequency adjustable to one decimal point.
2. Printing press rate - Operators can run the press at maximum printer speed (500 metres per min) with full conformance to quality requirements.
3. Safety - No safety risks with the use of the product.

4. Codes and regulations - food contaminants picked up during manufacturing due to the team's implemented design are rated at zero parts per million.

The team decided that these four metrics were the most important as they related most strongly to the client's needs. It is the team's goal to acquire the ideal metric value for these four target specifications.

2 Details of the Design

Four key elements will be investigated in this report: resonance in print cylinders, rotational imbalance of the print cylinders, doctor blade design, and the application of improved vibration-damping stickyback tape. In the investigation of roller balance, the team will employ a modal analysis which will illustrate typical resonant frequencies which are expected to arise with a given geometry. These resonant frequencies are suspected to be contributors to the bounce problem. The effect of rotational imbalance is outlined in Section 2.3. Improved doctor blade design can serve to aid in damping of the system as well as prevent hydroplaning and build-up of ink on the press during operation. Finally, the investigation of improved stickyback tapes can help to damp the system at the point of contact of the print roller. This allows for possible vibration reduction as well as reduction of localized deformations and stresses occurring as irregular patterns on the printing plate. This section begins with an investigation of how the adjustment of mass, stiffness and damping properties of a vibrating system affects the system's response.

2.1 Effects of Mass, Stiffness and Damping on a Vibrating System

In order to gain an understanding of how adjusting the various properties of the rollers will affect their performance, a simple hypothetical vibration analysis was performed. This analysis, using the built-in MATLAB software, Simulink, simulated a variable forcing function applied to a system, represented as an oscillatory sinusoidal function ranging from -1 to 1. This variable forcing function simulates oscillatory loading between two cylinders, which is what causes banding to occur. A constant input forcing function of 1 was also applied, simulating the contact force applied between two rollers. The constructed model is shown below in Figure 2.

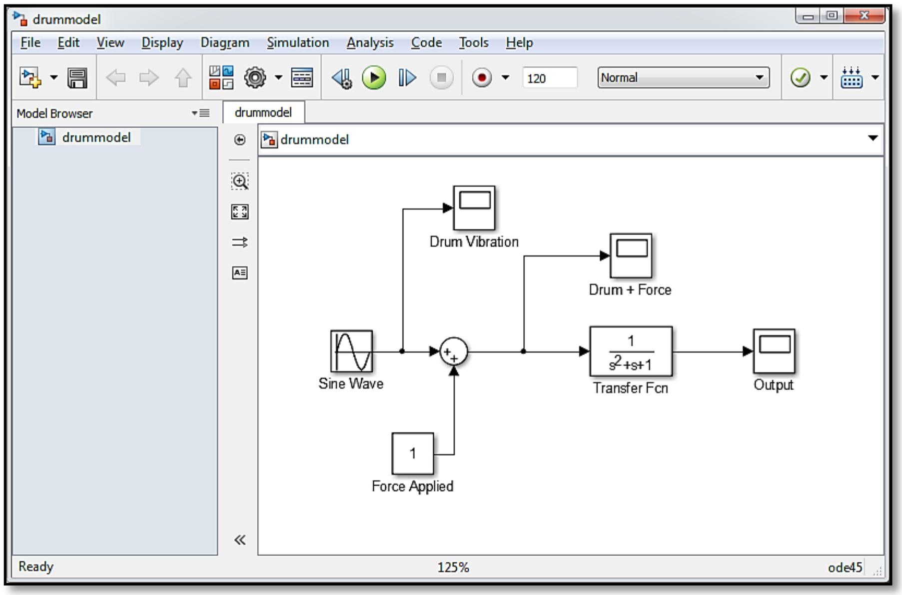

Figure 2: Simple Simulink model to simulate an oscillatory forcing function

Note that these forcing functions are non-dimensional – they are not specifically constructed to simulate the machines at Winpak. These forcing functions are then transmitted into a transfer function, which represents a system which possesses mass, damping and stiffness. The resulting plots are constructed in order to provide conceptual insight into how adjustments in mass, damping and stiffness affect the system. The base case, with all parameters set to 1, is shown in Figure 3 below:

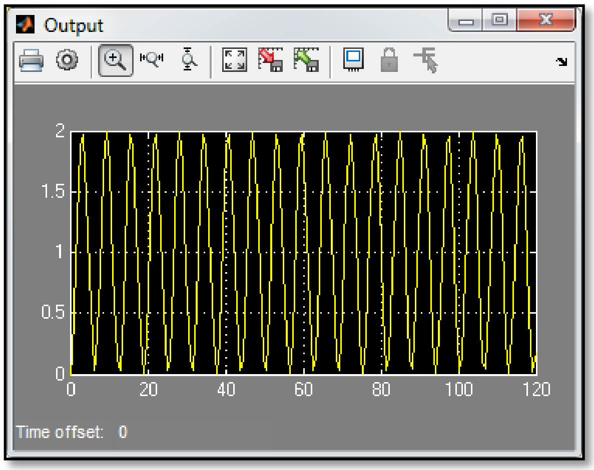

Figure 3: Force output in the base case

This case simulates an oscillatory force output which is at the critical threshold – the sinusoid just touches zero, which indicates that the contact force between rollers approaches zero at each cycle. At each instant the function approaches zero, it is recognized as an opportunity for variations in the ink application to occur. These troughs in the sinusoid represent locations where we would expect banding to begin to occur. We then double the mass of the system in order to observe how increased mass affects the response of the open-loop system.

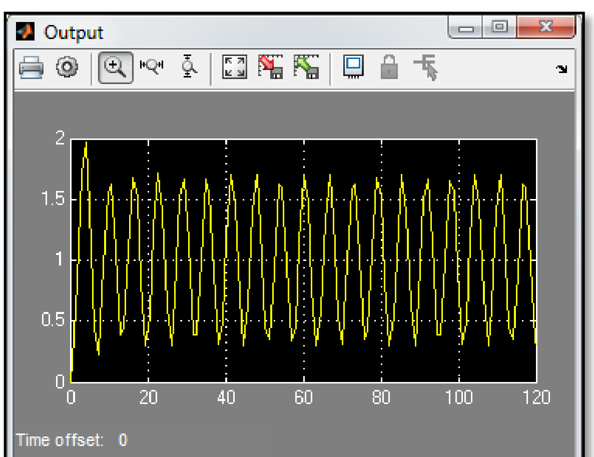

Figure 4: System's response upon doubling of mass

Figure 4 shows that an increase in mass causes the bandwidth of the steady-state response of the system to narrow. The system becomes more resilient to transient forcing functions. This can be understood intuitively – as something becomes more massive, it gets harder for the same input force to alter its state. The following figure, Figure 5, shows the response of a system that is 4 times as massive as the original:

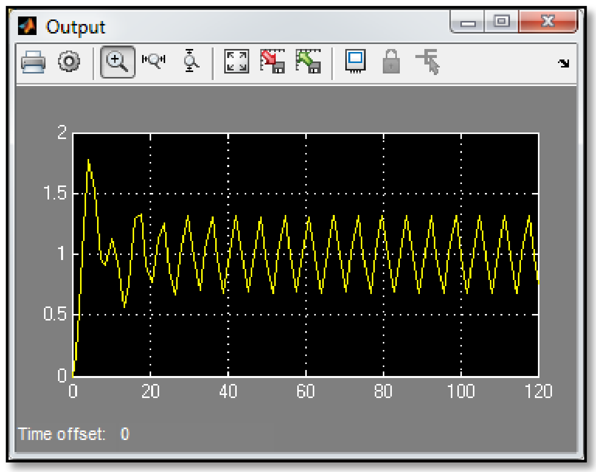

Figure 5: System's response upon 4 times the original mass

Figure 5, shows that the first peak no longer reaches 2, indicating that the system is now less responsive to the inputs. The steady-state response appears even narrower. Figure 6 shows the system's response when the mass is increased to 8 and 16 times the original.

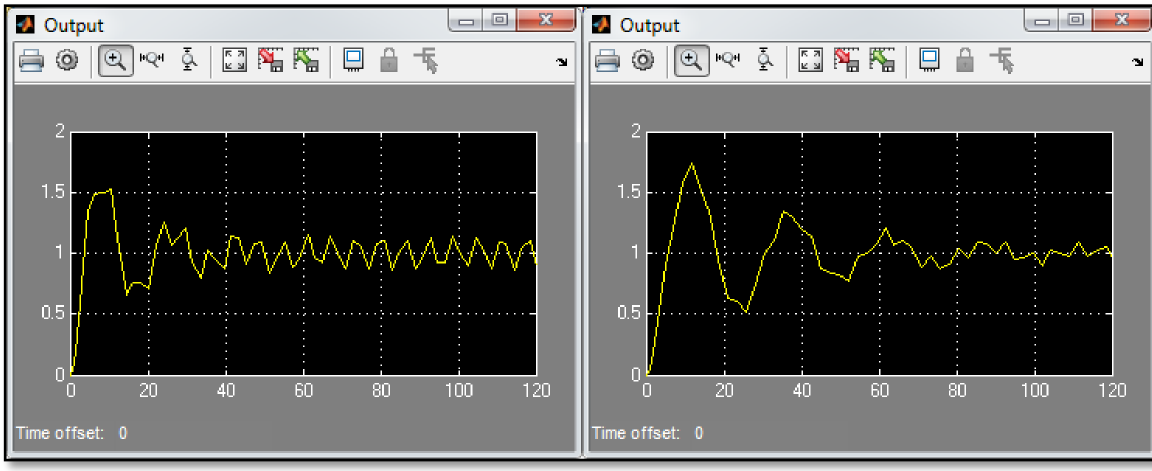

Figure 6: System's response upon 8 (left) and 16 (right) times original mass

The system converges closer to 1 as the mass increases further. The system's mass becomes even more resilient to transient forcing functions; the output tends toward the original forcing function of 1, which is the desired contact pressure between the rollers. It is observed, then, that the more mass the rollers possess, the more resilient they become to vibrational inputs.

Returning all conditions back to the base case, we next observe the system's response to increased damping. Recall Figure 3 as the base case scenario. Figure 7 shows the resulting response of the system upon increasing the damping 2 times and 4 times.

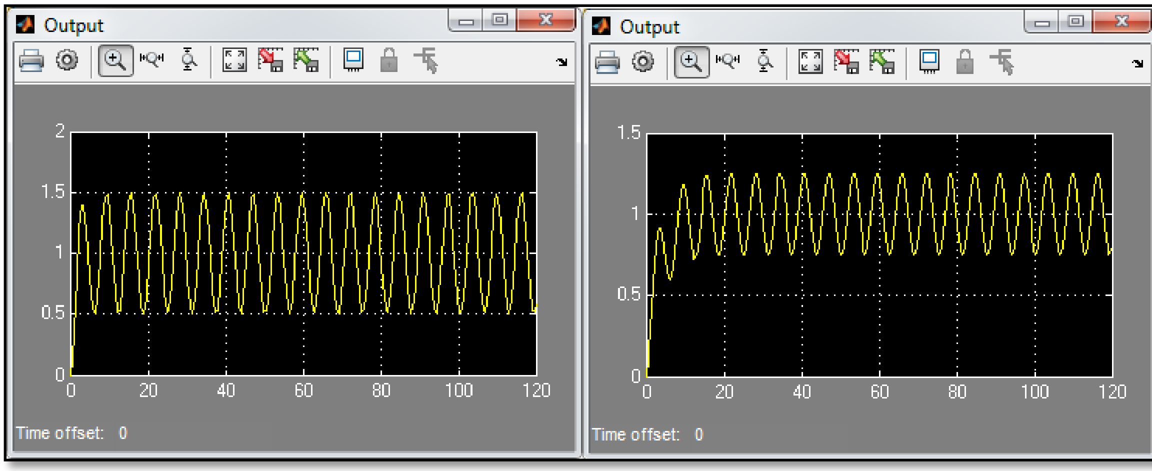

Figure 7: System's response upon 2 (left) and 4 (right) times the original damping

Figure 7 shows that the response improves much more rapidly upon increasing damping than increasing mass, as the bandwidth quickly narrows. The following figure (Figure 8) shows the response given 8 times and 16 times damping:

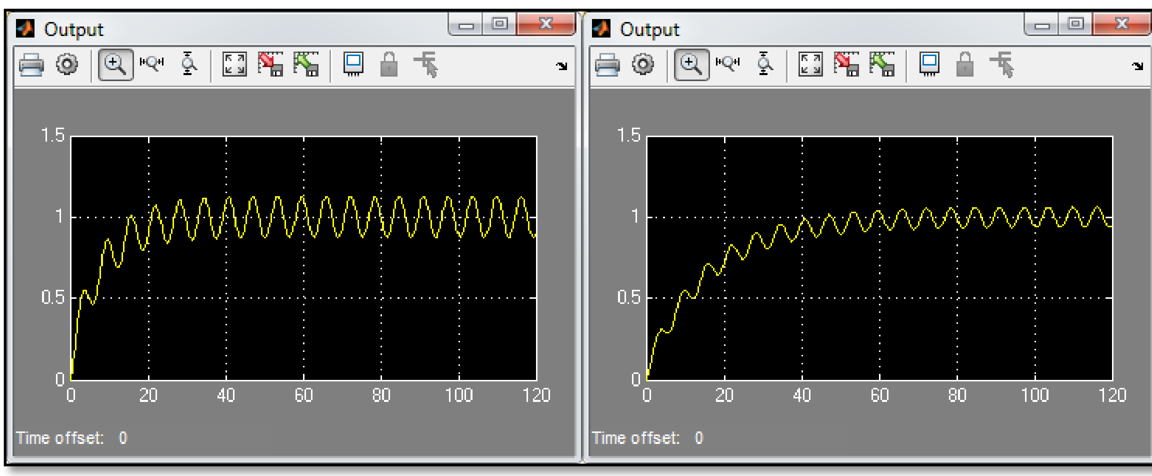

Figure 8: System's response upon 8 (left) and 16 (right) times the original damping

Finally, we again return the system to its base case and begin adjusting its stiffness.

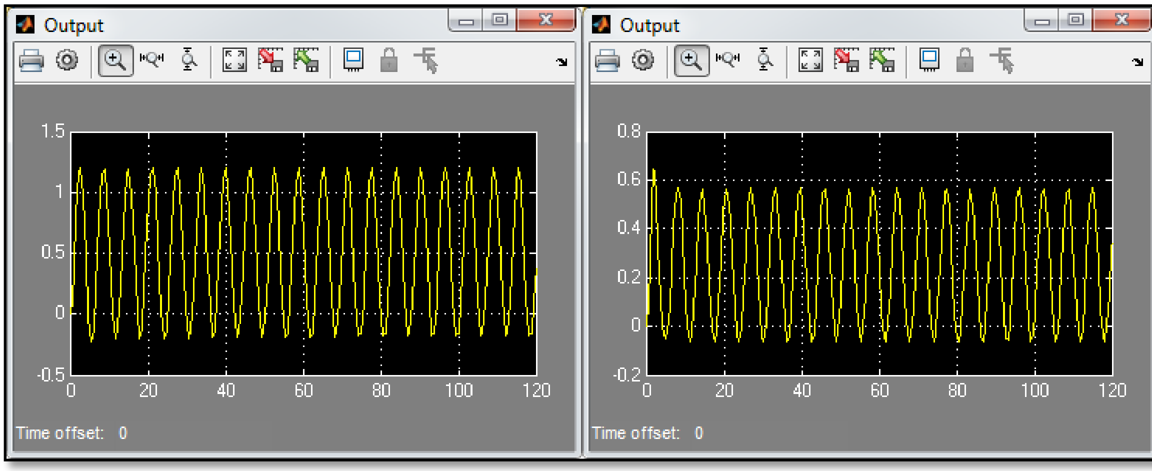

Figure 9: System's response upon 2 (left) and 4 (right) times the original stiffness

The increased stiffness in Figure 9 has caused the system to no longer oscillate about the constant forcing function of 1. Instead, the mean of the sinusoid begins to descend as stiffness increases, causing the force to drop below zero. This case would lead to increased banding in the print, since the rollers are now separated away from each other.

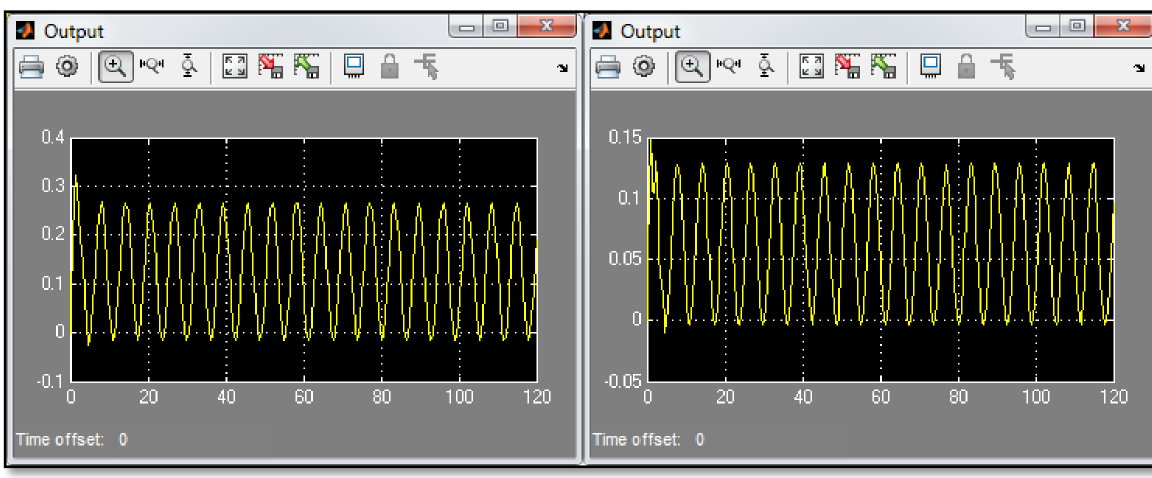

Figure 10: System's response upon 8 (left) and 16 (right) times the original stiffness

In Figure 10, we again see that the response of the system drops below zero, indicating bouncing. The bandwidth of the output continues to decrease, however the mean response continues to tend away from the input forcing function of 1.

Adjusting the mass, damping and stiffness properties of the system yielded different results, with damping clearly being the most beneficial in terms of system stability, predictability and uniformity of the overall force output. The increase of mass does indeed generate a more uniform response; however this model does not take into account the static deflection of a beam due to gravity. Given the increased risk of static deflection and the overall erratic behaviour of the system as mass increases, increasing the mass of the rollers is not deemed to be a feasible approach.

2.2 Bounce Caused by Cylinder or Sleeve Resonance

Roller vibrational modes cause the shape of the roller to change slightly during operation. The tolerances between the web material and rollers are very small and therefore any deflection of the roller could cause printing defects. A modal analysis of a cylinder with the following properties was performed in ANSYS to illustrate how a cylinder changes shape at certain frequencies:

- The cylinder has a 2.72 inch radius. The radius was taken from the ADAPTERFORPLATECYLINDERSLEEVE drawing provided by Winpak.
- The cylinder length is 57.87 inches. This dimension is taken from the ADAPTERFORPLATECYLINDERSLEEVE drawing.
- The cylinder is attached to smaller cylinders at each end. These act as supports for the cylinder. They are 1 inch in diameter, and 3 inches in length.
- The cylinder is assumed to be made of Structural Steel with the properties as seen in Table IV:

TABLE IV:
PROPERTIES OF STRUCTURAL STEEL USED IN PRELIMINARY ANSYS ANALYSIS

Property	Value
Density	7850 kg/m^3
Young's Modulus	200 GPa

The smaller diameter cylinders are constrained on the bearing surfaces in the radial and axial directions. The larger diameter cylinder is free in the radial, axial, and tangential directions. The model is shown in Figure 11.

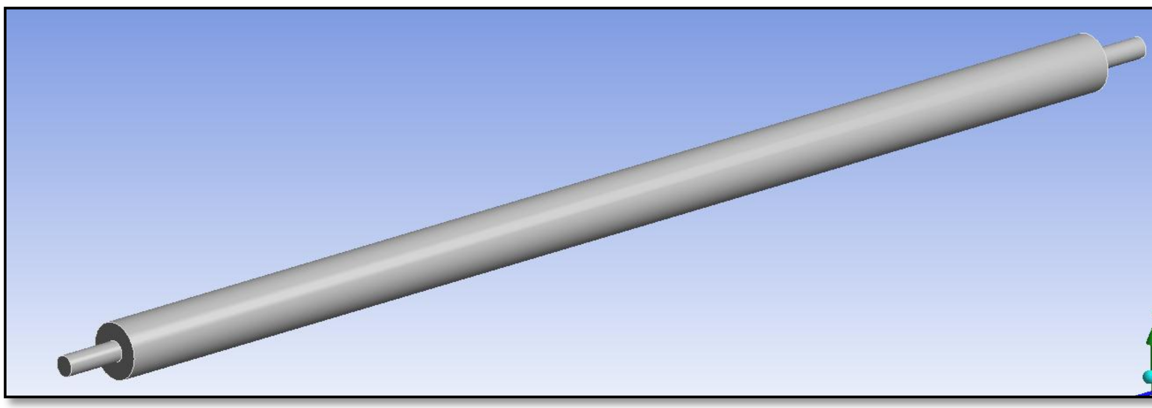

Figure 11: Preliminary cylinder model

The first three modes produced by the finite element analysis and their corresponding frequencies are listed in Table V.

TABLE V:
FIRST THREE MODES OF PRELIMINARY ANALYSIS

Mode	Frequency [Hz]
1	130.65
2	486.23
3	701.68

The angular frequency of a cylindrical object is given by the following formula:

$$\omega = \frac{v}{r} \quad (2.1)$$

Where v is the tangential velocity of the object and r is its radius. In this application, v is the speed of the printing press, and r is the radius of the roller. The previous equation can be arranged as follows to determine the print speeds at which each mode occurs:

$$v = \omega r \quad (2.2)$$

The corresponding print speeds are found using a radius of 1.36 inches and multiplied by the values from Table V and are summarized in Table VI:

TABLE VI:
PRINTING SPEED AT EACH MODE FOR PRELIMINARY ANSYS ANALYSIS

Mode	Frequency [Hz]	Print Speed (m/min)
1	130.65	270.8
2	486.23	1007.8
3	701.68	1454.3

Figure 12 to Figure 14 below show the first three mode shapes for the cylindrical model. Figure 12 shows the shape of the first vibrational mode of the cylinder. The area in red represents the region of greatest deflection, whereas blue indicates minimal deflection.

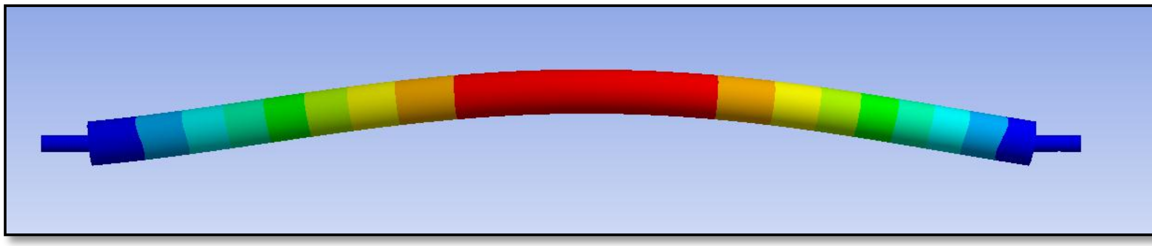

Figure 12: Mode 1 of preliminary cylinder model

Figure 13 shows the second mode of vibration of the cylinder. Again, the areas in red show the regions of maximum deflection, while the blue exhibits minimal deflection. Note the node at the centre – the cylinder oscillates symmetrically about this node on either side.

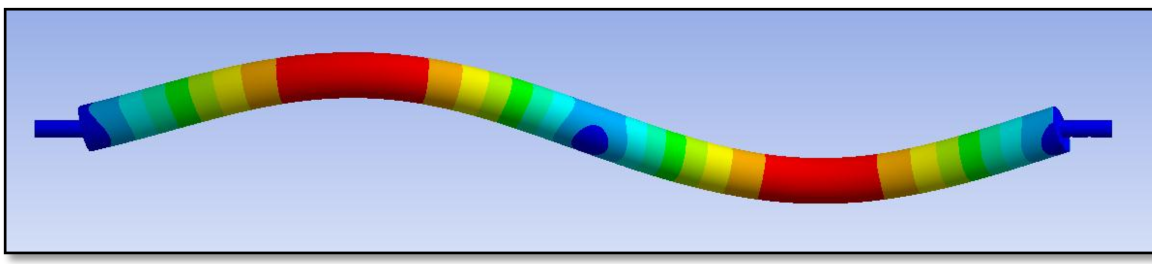

Figure 13: Mode 2 of preliminary cylinder model

Figure 14 shows the third mode of vibration in the cylinder. Two nodes appear, with three areas of maximum deflection. This vibration mode would be difficult to achieve, given that a print speed of approximately 1400 meters per minute is anticipated to be required in order to generate it, as seen in Table VI.

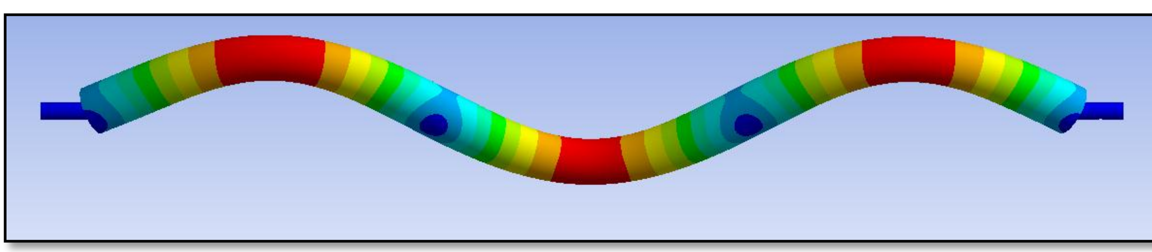

Figure 14: Mode 3 of preliminary cylinder model

When the printing press is operating at one of the modal frequencies there will be a loss of colour or quality in the red sections where the greatest deformation occurs, causing losses and gains in material contact upon each revolution. There will be a gain in material contact when the section with the greatest deflection is at the top, and a loss in contact when the section with the greatest deflection is at the bottom. These same mode shapes will occur in all cylinders with similar constraints. The type of material the cylinder is made of will change how much deformation occurs. A heavier, or more stiff cylinder will deform less than a lighter or less stiff cylinder.

The first mode occurs at a speed within the operating limits of the printing machine at a print speed of 270.8 metres per minute. The material passing over the centre of the roller may appear fainter relative to the rest of the image and print variationsat this resonant frequency. A more consistent image is anticipated to remain at the ends of the roller where it is more effectively constrained by the machinery. A finite element model is only an approximation of the cylinder itself, however, and does not take into account any effects that the rest of the machine or the environment places on the cylinder; the first mode resonant frequency is likely to vary with each machine setup. Given the occurrence of a first mode vibration problem in the printing process, the problem can be avoided by either slowing or speeding up the machine's operation – both solutions produce identical effects as the resonant frequency of the roller is then avoided.

Bounce from the metal cylinder on which the anilox sleeve is mounted is not likely since the print speed of the second and third modes are well above 500 metres per minute (Table VI), which is above the maximum operating limit of the machine.

The natural frequencies at which the vibration modes shown in Figure 12, Figure 13, and Figure 14 occur is approximated by:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{2.3}$$

where k is the stiffness of the material and m is the mass of the material. There are theoretically unlimited natural frequencies for the print rollers. Equation 2.3 is used to calculate the first natural frequency; all higher order natural frequencies are integer multiples of the first natural frequency. The natural frequency of the object is changed by either changing the stiffness of the material or changing its mass.

The modulus of elasticity (Young’s Modulus) of the individual materials which make up the anilox roller sleeves were not available, which makes accurate calculations to determine the natural frequencies of the anilox sleeves impossible. The Young's Modulus values of rubber, glass, and urethane, which make up the anilox sleeves, vary greatly; therefore modelling them after a similar type of rubber is not a valid assumption. Instead, we will calculate the stiffness of the sleeve based on the least stiff rubber related material and calculate the natural frequency for various printing speeds, then compare it to the stiffness of the four types of anilox sleeves for various printing speeds since we have the mass of each type of sleeve.

Equation 2.3 can be rewritten as

$$k = m{\omega_n}^2 \tag{2.4}$$

The mass is known, and we can substitute various operating speeds to determine if the k value is within reason for the type of material. The Young's Modulus of urethane can vary anywhere from 10 to 690 MPa [2] [3].

We can approximate the cylinder with the web creating a downward force as a beam in bending. In this case, the stiffness can be approximated as

$$k = \frac{AE}{L} \tag{2.5}$$

Substituting the area and length of the rubber roller, as well as 10 MPa as a sample Young's modulus based on the lowest Young's modulus found when researching urethane material properties, we obtain

$$k = \frac{(0.004069)(10x10^6)}{2.756} = 14{,}756\ N/m$$

We can compare this value to the ones in Table VIII below which provides calculations for what the k value should be for the material at different printing press speeds.

The manufacturer of the anilox sleeves, Rossini Sleeves, provided a spreadsheet which contained the dimensions of the anilox sleeves, the volume of the materials that make up the roller, and the total weight of the roller. Rossini Sleeves manufactures a rubber sleeve, an ‘evergreen’ sleeve, a ‘multievergreen’ sleeve, and a ‘dual thin’ sleeve.

Each sleeve is made up of different materials suited for various applications. They are summarized in Table VII.

TABLE VII:
MATERIAL COMPOSITION OF ROSSINI SLEEVES

Sleeve Type	Materials
Rubber	Fibreglass and rubber
Evergreen	Fibreglass, rubber, and urethane
Multievergreen	Fibreglass, urethane, and evergeen
Dual thin	Fibreglass

The different sleeves are shown in Figure 15.

Figure 15: Different anilox roller sleeves. Pending permission [1].

We can compare the calculated k value to the ones found in Table VIII. Table VIII lists what the k values should be for the given materials at different printing press speeds.

Table VIII evaluates each material at 100, 75, 50, and 25 metres per minute. The third column contains the outer radius of each sleeve from the spreadsheet provided by Rossini. The contents of the fourth column are calculated by multiplying the speed by the outer radius. The fifth column contains the total mass of each sleeve, which was taken from the spreadsheet provided by Rossini. The sixth column, containing the stiffness data, is calculated by multiplying the mass column by the frequency value squared.

TABLE VIII:
ESTIMATED STIFFNESS VALUES BASED ON PRINTING SPEED AND SLEEVE MATERIAL

[redacted]

None of the estimated stiffness values are close to the value of 14,756 N/m, which was the minimum stiffness value found for urethane. The stiffness value increases as the Young's Modulus value increases. For resonance and bounce to occur at the printing speeds in Table VIII, the stiffness value of the sleeve would have to be equal to the value in the furthest right column. Since the stiffness value of the lowest available Young's Modulus was 3.06 times greater than the highest value in the stiffness column, the sleeve is not expected to resonate and cause bounce at the speeds listed in Table VIII. The other materials that make up the sleeve, such as glass and rubber, are likely to be stiffer than urethane which will increase this difference even more.

In summary, it is anticipated that the metal print roller is susceptible to first-mode resonance at frequencies in the neighbourhood of 130 Hz, which translates to an operating speed of approximately 270 metres per minute. This is not a discrete frequency, but a likely target value of which the client should be cautious. Variations in operating conditions may cause a bandwidth of potential resonant frequencies. Based on stiffness analysis and material property projections, it is not expected that the interface of polymeric compounds to the metal rollers is a contributing factor to the occurrence of resonance.

2.3 Bounce Caused by Rotational Imbalance

Rotational imbalance occurs when the principal axis of inertia of an object does not coincide with the central geometric axis. This means that a cylinder may not rotate in a perfect circle due to mass eccentricities. In the case of the printing press, the web material may separate from the cylinder if the imbalance is large enough. Deflection from rotational imbalance is given by [4]:

$$X = \frac{mer^2}{M[(1-r^2)^2 + (2\xi r)^2]^{1/2}} \tag{2.6}$$

where m is the mass of the rotating element, e is the distance from the central axis to the axis of inertia, M is the mass of the entire machine, ξ is the damping ratio, and r is the ratio of the operating speed to the natural frequency of the rotating element. Resonance occurs when r is equal to 1. There are several ways to reduce rotational imbalance in the machine:

- Reduce the weight of the roller by replacing the roller with a less dense material, or by reducing the volume of the roller
- Reduce the distance from the central axis to the axis of inertia by ensuring that the roller is balanced
- Increase the mass of the entire machine
- Increase the damping ratio
- Change the operating speed to ensure r does not equal 1

Reducing the value of e will have the greatest impact since it is the only term which can realistically be zero. This is done by:

- Ensuring that the print roller does not have a mass imbalance
- Ensuring that the print template has uniformly distributed mass

The print template must be symmetric over any plane to ensure that there is no imbalance. The amount of deflection increases as the speed of the press increases, so any imbalance will become very severe as the speed of the press approaches the next resonant frequency. The following parameters are used as an example:

- m = 390.59 lb, which is the mass of the roller described at the beginning of Section 2.2.
- e = 0.005 inches, or an eccentricity 0.005 inches away from the central axis.
- The value of r is tabulated in increments of 0.05 from 0.1 to 1.
- M = 50 000 pounds, which is a very rough estimate of the weight of the machine.
- The damping ratio of ξ = 0.5 is assumed.

The values of X for r = 0.1 and r = 1 are shown in Table IX.

TABLE IX:
DISPLACEMENT VALUES FOR R = 0.1 AND R = 1

r	X (inches)
0.1	3.92537E-07
1	3.9059E-05

The displacement of the roller at r = 1 is 100 times greater than the displacement of the roller at r = 0.1 for an imbalance of only 0.005 inches. This stresses the importance of the rollers and template being balanced as well as possible. Each roller and template will have some slight imbalance on its own. Combined with each other, the total imbalance of the part will be much worse. If the imbalance is increased to 0.01, the ratio of maximum to minimum displacement stays the same, but the magnitude doubles.

The amount of displacement estimated from Equation 2.6 is very small. This equation, however, is for an ideal situation, and does not take into account factors such as roller wear or friction. The displacements in reality are likely to be bigger. The tolerances used in the printing process at Winpak are as small as a few thousandths of an inch, which is not significantly larger than the calculated value for r = 1. It is possible that imbalance may be causing bounce in the printing press. The imbalance will be worst when r = 1, and should disappear when the print speed is increased so r does not equal 1.

2.4 Doctor Blade

An improved doctor blade is one of two proposed 'band-aid' fixes for Winpak's bounce-related flexographic printing problem. The term 'band-aid' is used to suggest that the goal of these two possible solutions is not to eliminate the inherent vibration created by their aging flexographic printer, but to damp the effect of the vibration such that the occurrence of bounce is eliminated from Winpak's printing result [4].

2.4.1 Doctor Blade Design Theory

A doctor blade is a thin strip of metal which is used to remove excess ink from the anilox roller. The main design goal when manufacturing a doctor blade is straightness of the blade such that the blade is in constant contact along the length of the anilox roller. The doctor blade is fitted into a doctor blade chamber which houses the blade. When the doctor blade is fitted into the chamber, a portion of the blade is protruded from the base of the chamber to come into contact with the anilox roller. The doctor blade chamber can be modified to vary the angle of contact between the anilox roller and the doctor blade. Most manufacturers recommend a pressure angle of 60 degrees (measured from the horizontal), but angles anywhere from 55 to 65 degrees are used to help aid in correcting any printing errors and aid in minimizing contact wear for both the doctor blade and the anilox roller [4]. The contact force between the blade and the anilox roller should be minimized to allow for minimal wear on the anilox roller and doctor blade. The contract force must however be great enough to allow for all excess ink to be removed. The figure below shows a traditional doctor blade setup where it is in contact with the anilox roller.

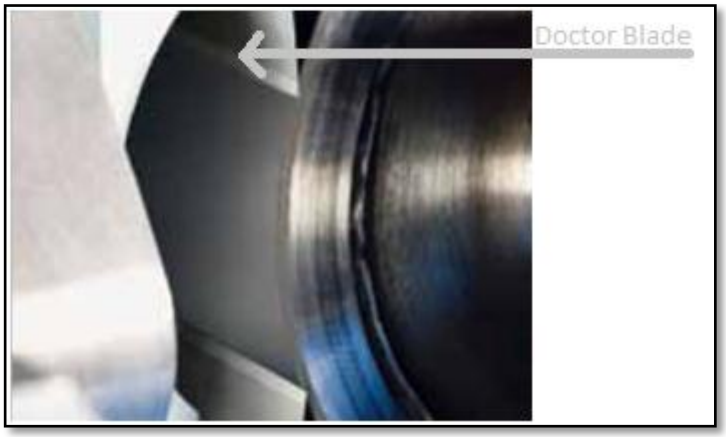

Figure 16: Common Doctor Blade Setup with Anilox Roller. Used with permission [5].

A consequence of excess contact force between the doctor blade and the rotating anilox roller is that the doctor blade deflects such that ink drools underneath the blade, causing the appearance of undesired excess ink in various areas of the print (Figure 17) [4]. This problem only presents itself when there is excessive contact force between the anilox roller and the doctor blade and when the base of the blade is not stiff enough to withstand the hydrodynamic forces created by ink building up against the doctor blade [4]. Figure 17 demonstrates how ink splits when deflection of the doctor blade occurs.

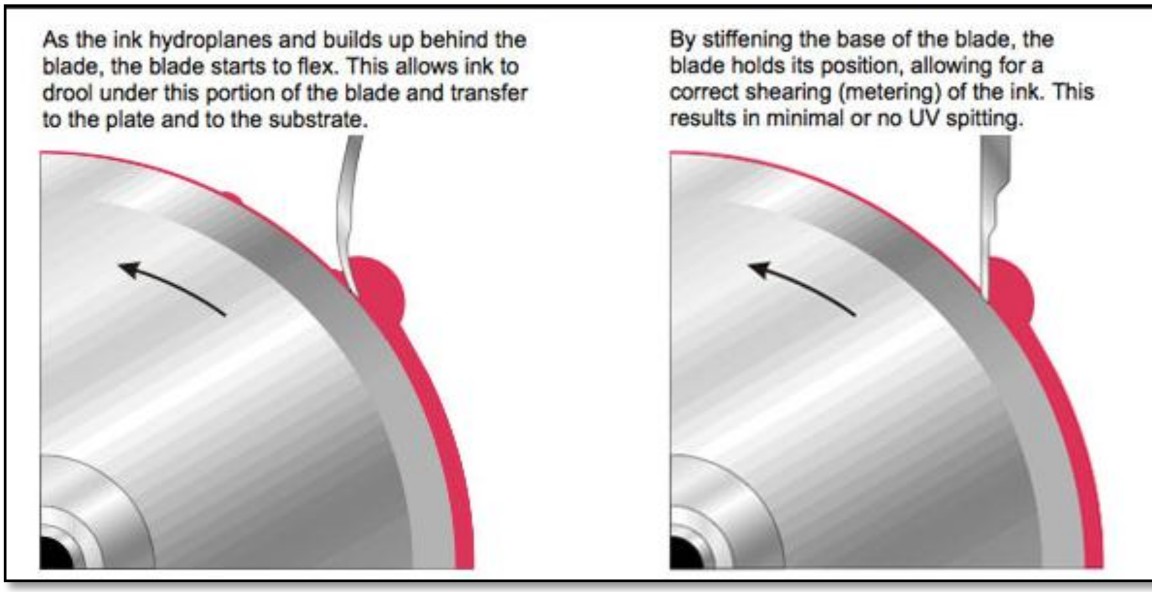

Figure 17: Comparison of Blade Stiffness with Respect to Ink Splitting. Used with permission [5].

Chatter marks and bounce-related printing errors are common occurrences in aging flexographic printers, especially at higher printing speeds [4]. Bounce-related printing errors add to the waste of material. When errors in print results are experienced, the rates at which the flexographic printers are running are slowed down until the effects of bounce are no longer visible (typically reducing printing rates by approximately 20%), which decreases production rates [1]. The goal of designing a blade to aid in reducing bounce-related printing errors is not to eliminate the vibrations that are present in aging flexographic printers, but to act as a shock absorber to dampen the vibrations to eliminate the occurrence of bounce. The concept behind the design is that any vibrations occurring in the anilox roller and doctor blade chamber can be damped by the doctor blade design and configuration by ensuring constant ink transfer to the anilox roller. By eliminating bounce from the printing results, less waste and increased printing rates (up to 500%) can be experienced [1].

2.4.2 Doctor Blade Design

Figure 18 explains the terminology used when describing the doctor blade dimensions.

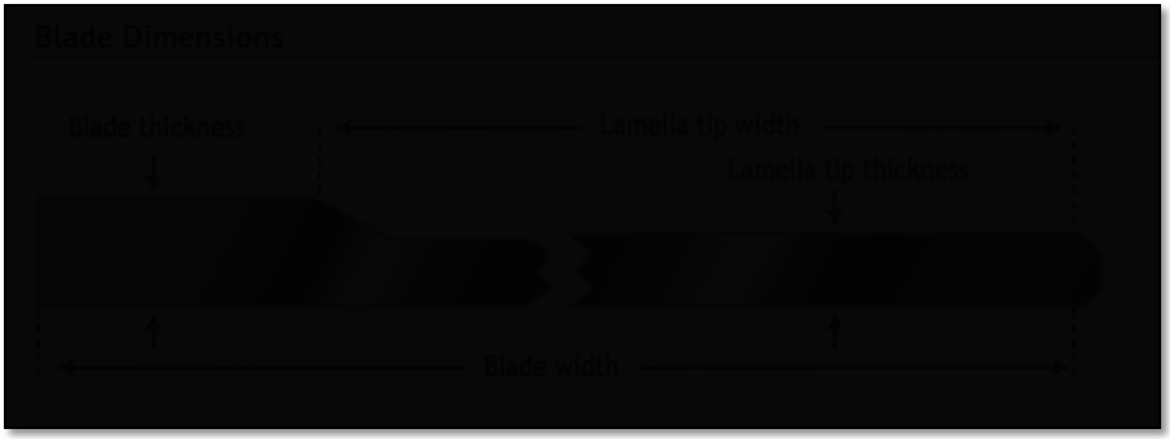

Figure 18: Doctor Blade Nomenclatures. Pending permission [6].

The doctor blade used by Winpak has having a blade width of 35mm and a blade thickness of 0.15mm [7]. This is the raw data provided by Winpak and does not include the use of a lamella (see Glossary of Terms, page v). Figure 19 showcases the general shape of a conventional blade.

Figure 19: Conventional Doctor Blade. Pending permission [8].

The proposed design is based on Winpak's original doctor blade dimensions to ensure compatibility with their flexographic printing machine. However, small adjustments can be made to improve performance. These design changes include:

- Addition of blade lamella and decrease of blade width to allow for additional flexibility to absorb vibration.

- Increasing the blade's thickness to add stiffness to the base of the design to prevent ink splitting.
- Inclusion of a highly-polished edge to ensure constant contact of the blade across the length of the anilox roller.
- A rounded tip to ensure a constant contact point.
- A rounded transition from the lamella to the main portion of the blade to decrease stress concentration.

SolidWorks models were produced in order to create an optimum design to damp any vibration in the working area of the doctor blade and anilox roller. Features such as the blade width, lamella length, lamella tip thickness and blade material were adjusted to create the optimal design. The final optimal design is shown in Figure 20, Figure 21 and Figure 22.

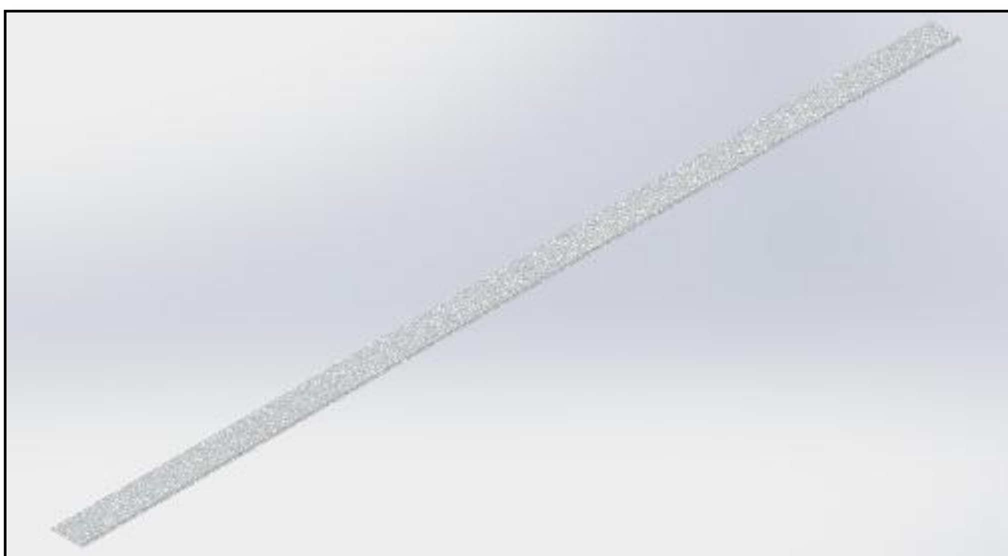

Figure 20: Final Doctor Blade Design (Isometric View)

Figure 21: FInal Doctor Blade Design (Cross Section View)

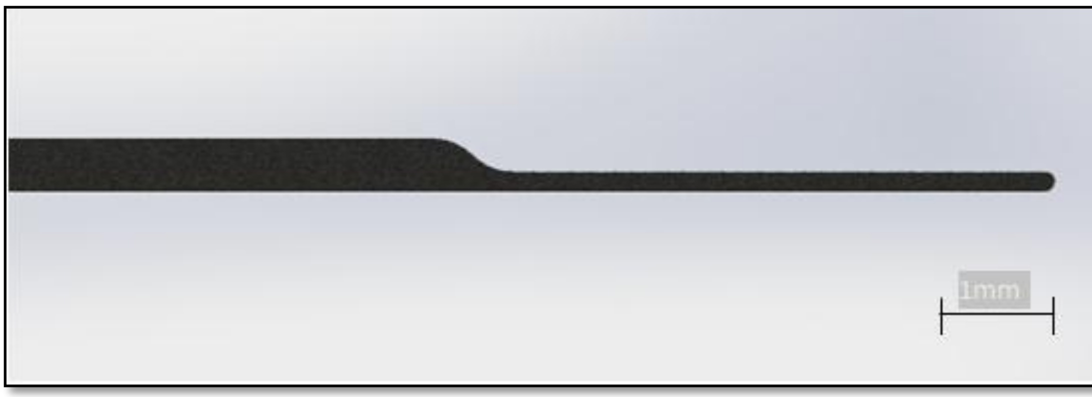

Figure 22: Final Doctor Blade Design (Cross Section of Lamella View)

The final blade dimensions were based within industry standards of doctor blade dimensions, while conforming to our specific design requirements (Figure 23) [8]. The final cross-section dimensions for the proposed doctor blade design are shown in Figure 23. The only undefined dimension to consider is the length of the blade; this will be dependent on the chamber in which the doctor blade is housed.

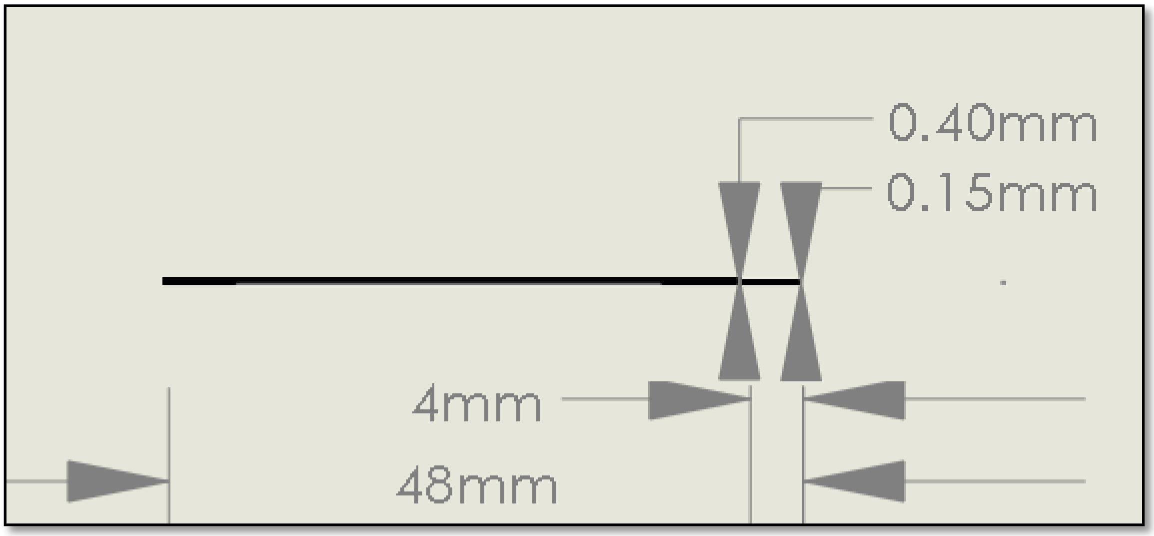

Figure 23: Designed doctor blade dimensions (Cross Section View).

The blade is to be clamped into Winpak's existing doctor blade chamber shown in Figure 24. The amount of blade width to be clamped, as recommended by the team, is approximately 24mm. This recommendation is based on industry standards, but this can be adjusted to improve upon blade performance if necessary [8]. Figure 24 illustrates the chamber that Winpak uses to hold the doctor blade.

Figure 24: Winpak's Doctor Blade Chamber. Pending permission [7].

The material used in the final design was chosen to be ‘grade No. 2D’ cold rolled stainless steel (modulus of elasticity of 28x10^6 psi) [9]. This material was chosen since stainless steels are commonly for doctor blades due to their high corrosion resistance-properties, which adds to the lifetime of the blade and reduces costs [9]. The material was chosen to be cold rolled since cold rolling increases strength, improves surface finish and holds tighter tolerances [9]. Additional strength will allow for minimal deflection such that ink splitting does not occur. Additional strength also means a decrease in ductility that may negatively affect the ‘shock-absorbing’ features of the blade. However, the addition of an elongated lamella ensures that a decrease in ductility will not cause a problem in the proposed doctor blade's function.

2.4.3 Cost

Cost of the design will vary based on care and maintenance of the blade when in use. If there is more force applied between the doctor blade and the anilox roller than needed to remove all excess ink, then excess wear on the blade will occur. This means that the blade will need to be replaced more frequently. Other sources of wear that will inherently add to costs include: abrasion from foreign particles, use of abrasive ink pigments, corrosion from oxidation, or use of inks that are beyond acidic or alkaline standards [10]. Since the doctor blade being designed needs very specific manufacturing processes such as cold rolling, calculating the true cost of the design would result in a very rough estimate. The best way the team can calculate the approximate cost of the doctor blade is to compare it to similar industry solutions. The costs obtained for a similarly designed blade made by MDC that has a design based on a long, flexible lamella is quoted at $1600USD-$2300USD per100 meters of doctor blades [10]. This cost per 100 meters of blades would result in an average cost of approximately $30/blade for Winpak's use. This will be a recurring cost since the blades will need replacement once excess wear occurs. However, $30 per blade is a very small price to pay if Winpak can increase their production rates. Winpak currently runs their flexographic printers at one fifth of their desired print rate of 500 meters per minute [1]. Production rates could be increased up to 500% if bounce is completely eliminated from the proposed design. Figure 25 below showcases the MDC StableFlex, which is the blade used in our cost analysis. This blade could be applied to Winpak's flexographic printers since it can be made with varying dimensions to satisfy client needs [5].

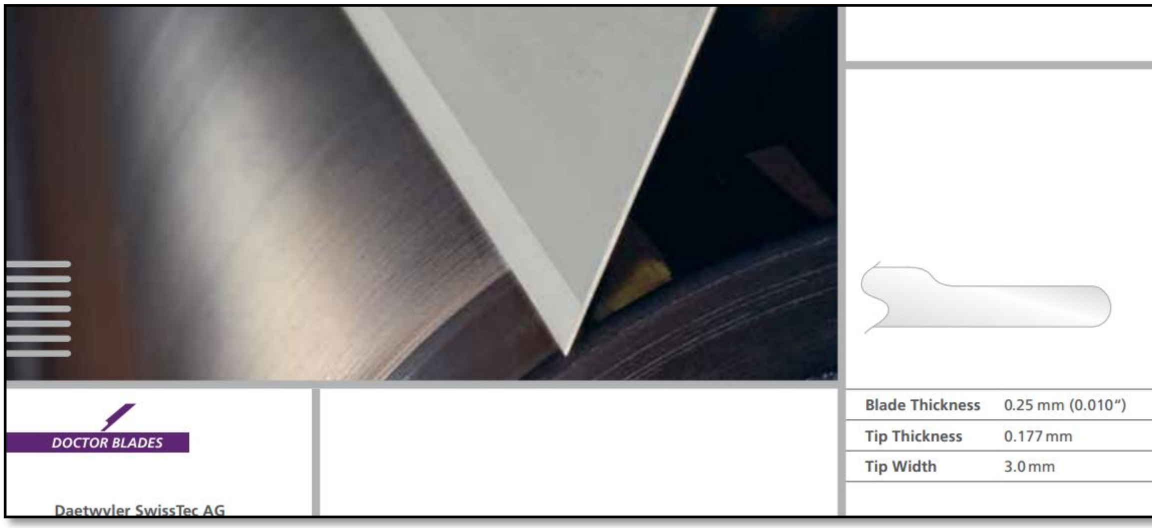

Figure 25: Daetwyler MDC StableFlex Dimensions. Used with permission [5]

2.4.4 Doctor Blade Design Summary

The doctor blade designed by the team has been modeled to aid in damping vibrations occurring in the area of the anilox roller. The dimensions and material of the blade were optimized through use of SolidWorks and are listed in Table X.

TABLE X:
IMPORTANT FEATURES OF PROPOSED DOCTOR BLADE DESIGN

Feature	Dimension
Blade width	48mm
Blade Thickness	0.4mm
Lamella Width	4mm
Lamella Thickness	0.15mm
Overall Blade Length	Dependent on Doctor Blade Chamber being used within
Clamping Distance	24mm (Half-distance of blade width)
Material	Stainless Steel ($E=28x10^6$ psi)[9]

With the design in mind, the team realizes that Winpak is not equipped for the manufacturing of doctor blades and would benefit from having the blade made for them.

Daetwyler is a company that would be able to supply Winpak with bounce-reducing doctor blades which are similar to the design. Therefore, it is also recommended that Winpak contacts Daetwyler to inquire about their bounce reducing doctor blade called the MDC StableFlex (described on page 34).

2.5 Stickyback Tape

Stickyback tape (i.e., mounting tape) is a main component in a flexographic printer because it connects the printer's printing cylinder to a photopolymer printing template (see Figure 27). By making the stickyback out of vibration-absorbing material, the effects of vibrations where ink is transferred to the final product's packaging can be damped. Winpak currently uses stickyback tape made by 3M [1]. 3M currently develops stickyback tape that aids in vibration reduction. Since Winpak has developed strong relations with 3M, it is likely advisable that Winpak experiment with 3M's vibration reducing stickyback tape production line. These tapes are called 'Solid Printing Tapes with Foam Carrier' and 3M states that these versions of tapes create high-density ink coverage as well as a cushion surface to absorb vibration [11].

2.5.1 Recommendation of Alternative Stickyback Tapes.

The series of stickyback tapes used by Winpak are Series 10, 12, and 19 [1]. The following content illustrates the properties of the different series of stickyback that Winpak uses.

Series 10 is used when solid and halftone lines are mixed on the photopolymer plate. When compared with 3M's other series of tape, series 10 is very flexible and has a wide range of adhesive options. Series 10 foam tape is a standard, all-purpose foam that can be used for any printing job that comes into Winpak [12].

Series 11 is used for finer dots to produce a sharper image. The main feature of this series is that it allows for controlled ink transfer at high printing rates [over 100 metres per minute]. The benefit of this series of tape is that the tape can be positioned, adjusted and repositioned with ease when attaching the plate to the printing cylinder. Another important feature is that the photopolymer plate side adhesive of Series 11 stickyback tape is strong enough to hold a photopolymer plate through long production runs with stable positioning. The photopolymer plate can be removed cleanly from the tape when the printing job is done and then be used for future printing jobs [12].

Series 19 is used when process and highlighted half tones are combined with fine lines or small solid areas on a small photopolymer plate. Series 19 is denser than Series 11 and is used to create clean lines and transfer sufficient ink without significant added dot gain. Series 19's foam is shaded pink for easy identification. Just like Series 11, Series 19 stickyback tape allows for the photopolymer plate to be removed, cleaned of ink, stored and reused [12].

Although Series 10, 11 and 19 have appropriate properties for standard flexographic printing application, they do not effectively resist bounce. It is recommended that alternative types of stickyback tape be used to damp the vibrations present in Winpak's flexographic printer. Series 10, 17 and 18 are investigated for this specific case.

Series 17 is used when line, solids, and opaque background colour and can be used during high printing rates (over 100 metres per minute). Series 17 is made with a cushion-like material to aid in absorbing vibrations. Series 17 is able to produce rich half tones in the resulting print if required. The foam colour of Series 17 is teal green for clear identification [12].

Series 18 performs similar functions as Series 17 in terms of incorporating a cushion-like surface to aid in vibration absorption. The difference is that Series 18 tape is used when the photopolymer plate contains more solids in a combination of both solids and half tones. Series 18 is identified by a blue foam color for easy identification [12]. Figure 26 below shows the colour intensity and dot sharpness results of Series 10, 11, 19, 17, and 18 after printing.

Figure 26 Results of Series 10, 11, 19, 17, and 18 after printing. Pending permission [12].

Both Series 17 and 18 can potentially minimize bounce due to their cushioning structure. This structure provides an excellent shock-absorbing effect. When the printing surface contacts the printing plate, vibrations are created as the printing plate rotates and hits any sort of uneven surface. This phenomenon aids vibration in Winpak's flexographic printer and results in bounce marks in the printed product, which are unacceptable by industry standards. Hence, both Series 17 and 18 are recommended since they encompass a cushion-like structure that aids in damping vibration as well as allowing for operation at higher printing rates (up to Winpak's desired printing rate of 500 metres per minute) [12]. Figure 27 below illustrates how 3M's Cushion Mount Tapes can aid in damping vibration.

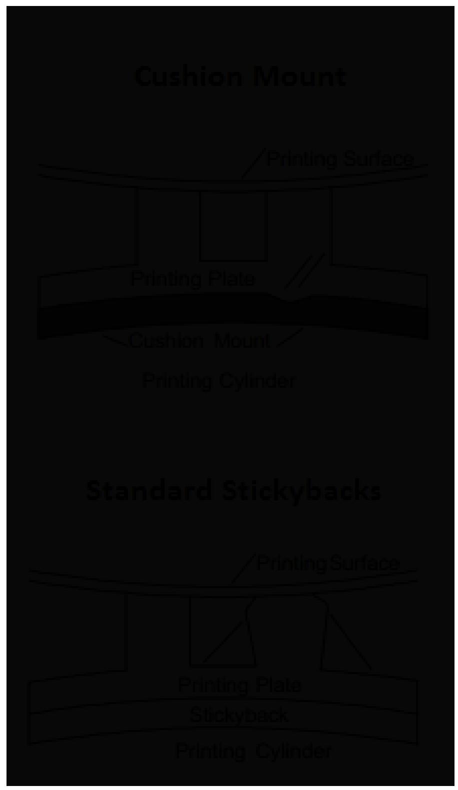

Figure 27: Comparison between Cushion Mount and standard stickyback tape. Pending permission [13].

Figure 27 shows that 3M's Cushion Mount tape absorbs sudden force or vibration such that the resulting printing quality is not likely to be affected. Using Series 17 and Series 18 of 3M's stickyback tape in conjunction with the team's design of a shock-absorbing doctor blade will greatly aid in damping vibrations and will result in minimized product waste, increased production rates and increased profits.

3 Conclusions

Printing deficiencies can occur at approximately 270 meters per minute based on a modal analysis of a printing cylinder performed in ANSYS. However, finite element models do not take all real world effects such as friction and other environmental effects into account. This will change the speed at which the first vibration mode occurs, which is where bounce will occur. The best way to avoid this issue is to increase or decrease the operating speed so the press does not operate at the speed which the first vibration mode occurs.

Imbalance in the machine is also a likely cause of bounce. It is unlikely that all rollers, and components mounted on rollers are perfectly balanced. Deflection of the web material from the print roller will occur as the speed of the printing press approaches the natural frequency where resonance occurs. The print template has different designs from print job to print job, and a slight imbalance could cause major deflection when the press operates at a resonant frequency. The best solution to avoid this is to change the speed of the press so it does not operate at a resonant frequency. Bounce will occur at the resonant frequency, but should not occur when the print speed is increased above the resonant frequency.

Through various different forms of analysis on what are likely causes to the bounce phenomenon Winpak is experiencing in their flexographic printers, it was found that there are two suggested measures to solve Winpak's problem. These two solutions can be summed up as either trying to eliminate the vibrations that are causing bounce to occur or using damping techniques that greatly lessen the effect of vibration, thus eliminating the bounce effect. The first damping recommendation is to switch the currently used 1120, 1220, and 1920 versions of 3M's stickyback tape to 3M's 17 or 18 series of stickyback tape, which act as a cushion and absorb vibration stemming from the flexographic printer. The second recommendation in terms of damping is to replace the current doctor blade with a blade that is designed to act as a shock-absorber in the area of the doctor blade chamber and anilox roller. By using a doctor blade with a long flexible lamella and a highly-polished tip, the blade was found to be able to 'ride' with the vibrations and therefore would decrease the possibility of experiencing bounce in the printing results. The team suggests either going with their design but since Winpak is not setup for manufacturing doctor blades, the team further suggests that Winpak invests in the MDC StableFlex doctor blade made by Daetwyler. The StableFlex is a blade similar in design methodology to that of the team's and is an industry-proven solution to solving bounce related issues in flexographic printers.

References

[1] C. Parker, Interviewee, *Winpak Printing Division Site Tour.* [Interview]. 12 September 2013.

[2] Matbase, "Urethane Rubber," 2013. [Online]. Available: http://www.matbase.com/material-categories/natural-and-synthetic-polymers/elastomers/material-properties-of-urethane-rubber.html. [Accessed November 2013].

[3] efunda, "Polymer Material Properties," 2013. [Online]. Available: http://www.efunda.com/materials/polymers/properties/polymer_datasheet.cfm?MajorID=pu&MinorID=1. [Accessed November 2013].

[4] "Doctor Blade," PrintWiki, 2007. [Online]. Available: http://printwiki.org/Doctor_Blade. [Accessed 25 November 2013].

[5] "Flexographic Doctor Blade," Daetwyler, 15 January 2013. [Online]. Available: http://daetwyler.co.uk/doctor-blades/doctor-blades-flexo/. [Accessed 20 October 2013].

[6] AD Doctor Blades, "Doctor Blades," 2012. [Online]. Available: http://www.ad-doctorblade.com/blade-dimensions/. [Accessed 25 November 2013].

[7] Holscher and Windmoller, "Miraflex Instruction Manual," Lengerich, CD-ROM.

[8] "Product Usage," Mycron, [Online]. Available: http://www.doctorblade.co.in/product.php. [Accessed 23 Novmber 2013].

[9] W. Roberts, "Cold Rolling," in *Cold Rolling of Steel*, Taylor & Francis, 1978, pp. 88-90.

[10] "Switzerland MDC Lamella Doctor Blade," Alibaba, 2013. [Online]. Available: http://www.alibaba.com/product-gs/1047571748/Switzerland_MDC_Lamella_Doctor_Blades.html. [Accessed 24 November 2013].

[11] "Flexographic Mounting System," 2005. [Online]. Available: http://www.3M.com/industialtape. [Accessed 30 November 2013].

[12] "3M Flexographic Mounting Tapes with Combination Printing," 3M United Kingdom PLC, 2003. [Online]. Available: http://multimedia.3m.com/mws/mediawebserver?mwsId=SSSSSu7zK1fslxtUMxmvn8_eev7qe17zHvTSevTSeSSSSSS--. [Accessed 20 November 2013].

[13] "3M Cushion-Mount," 3M United Kingdom PLC, March 1996. [Online]. Available: http://multimedia.3m.com/mws/mediawebserver?mwsId=66666UF6EVsSyXTtoXM

tlXF6EVtQEVs6EVs6EVs6E666666--&fn=949.pdf. [Accessed 30 November 2013].

APPENDIX A: Adapter Plate Drawing

The following schematic, provided to the team by Winpak, was used to ascertain roller dimensions in the team's analysis. These dimensions were used in order to produce volumetric and geometric information used in resonance and imbalance calculations, as well as finite-element analyses. All schematics are property of Windmoeller & Hoelscher Corporation and have been provided by Winpak Ltd. in confidence, and may not be reproduced or distributed.