Influence of Australian Research on Conveyor Technology

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Abstract

Research on belt conveyors in Australia is reviewed in an historical context. By the 1980s belt conveying and manufacture was well established. Mining and bulk handling industries generally relied on research from offshore institutions and companies, however, mines required a better understanding of complex conveyor issues. CSIRO commenced studies of belt problems in the late 1970s and during the next decade, the research resulted in new knowledge and technological developments on conveyor design, mechanics and reliability improvement. Early research work at Newcastle University on economic models for conveying, became coupled with CSIRO research, resulting in ongoing joint activity to this day. A review of conveyor research in Australia after 1970 discusses some of the early technical milestones that advanced the conveying and bulk handling industry.

1. Introduction

The history of troughed belt conveyor invention and development began in the late 1800s. As early as 1896, Thomas Robins Jnr USA developed conveyors using idlers. By the mid-1900s, troughed conveyors were the accepted method to handle bulk materials such as coal, ores and grain. By 1920, conveyor belting for troughed application was constructed of natural rubber and cotton duck reinforcement. Goodyear USA not only manufactured fabric reinforced rubber belting, but in 1942 also constructed the first rubber belt containing steel cords as the tensile member.

Australia quickly adopted the use of troughed belts manufactured by UK, European, Japanese and US companies. Cable Belt UK also supplied steel rope-based conveyors to Australia. In relation to the more widely used troughed conveyor system, no real “standardized” method existed to deal with the mechanical design of the belt conveyor, given so many suppliers were producing different products.

ANSI/CEMA worked to produce a conveyor design document which was published by CEMA in 1966 [1]. The CEMA handbook set out power and tension equations that could be used to calculate losses due to rolling, lift of belt and material, pulley and idler losses. This document continues to evolve.

Use of synthetic rubbers and fabrics such as polyester, rayon and nylon were applied to belting manufacture during the post-WW2 era of the 1950s. German research commenced about 1950 and largely concentrated on rolling loss and friction analysis, power prediction, splicing and drive methods. In 1956, Phoenix Germany made steel cord belting, and by 1957 BF Goodrich made steel cord belting. Steel cord belting became the high strength standard for long, high tonnage conveyors, though not without mechanical and operational issues. Academic research on belt conveyor mechanics was centered in Germany between 1950 and 1980.

During this period, research at Hannover University led by Vierling, Oehmen and Lachmann formalised conveyor mechanics and transport theory. In 1954, Lachmann published the first paper on troughed belt flex resistance [2], and in 1956 the rolling resistance of a belt was published by Vierling [3]. Continuing research on additional conveyor loss mechanisms and drive lagging methods were published by various authors including Behrens, Schwartz, Bahr and Grimmer [4].
Between 1970 and 1980, Hager, Funke and Oehmen in Germany investigated rolling friction, drive starting using head and tail motors for large capacity conveyors in lignite mines. Funke (TU Hannover) published a Dr-Ing Dissertation on the start-stop dynamic behaviour of conveyors [5]. Between 1978 and 1983, Spaans and Jonkers (Holland) conducted studies on indentation rolling losses of belts on idlers. Most of the early research resulted in production of the various Standards that led to DIN 22101 in 1982. Other authors of this era can be searched on the Internet.

With regard to belt manufacture and standardisation, Australian Standard AS B3 (based on a British Standard) for textile reinforced belting was first published in 1929 as part of the B-Mechanical Engineering series in Australia. Re-designated several times up to 1969 (as AS B6.1) [6], the document became AS1332 in 1982. By 1974, Australia produced AS 1333 for Steel cord belt manufacturing.

Increased use of electronics for measurement and control allowed researchers around the world to more thoroughly study conveyor mechanics. Bulk material handling with large capacity fabric and steel cord belts was well established in Australian coal and ore mines by the 1970s, although these conveying systems were not problem free. Continuous effort by mine engineers to modify or rectify conveyors to improve reliability was widespread across the country.

Australia responded to mining industry needs in the late 70s by fostering government organisations and universities with research funding. The paper highlights some of the research milestones from Australia, from the author’s perspective, that led to new directions for improved conveyor design and operation.

2. Conveyor Research – An Australian Perspective

During the 80’s a new era of conveyor research commenced in Australia in response to mining industry needs. Many organisations existed or were formed to support the industry including CSIRO, ACIRL, ACARP, NERDDC, AMIRA, Standards Associations, belt manufacturers, universities with mining departments, State mines and safety departments. Following industry requests for support, CSIRO was one organisation that provided a platform for interaction with industry to develop scientific and engineering solutions to reduce conveyor failure and downtime.

On one front, research commenced at CSIRO National Measurement Laboratory in early 1979 (Harrison) to investigate conveyor usage issues. Without reference to European research effort, Australian research started by developing instrumentation for conveyor measurement, from which evolved mathematical descriptions for conveyor vibrations, dynamics and design. A broad spectrum of problems and mechanical issues with conveyors began to be addressed.

On another front, research at Newcastle University in the late 70s by Roberts et al investigated conveyor optimization based on economic considerations. Application of bulk handling and storage research, together with flow property studies, led to a very wide research direction within the University’s TUNRA Bulk Solids which had existed since 1975. In 1980, collaboration between Roberts and Harrison commenced with broad research directions involving bulk handling, initiating Australian research in belt conveying and bulk materials handling at an academic level.

2.1 Steel Cord Belt Corrosion Monitoring - The cbm System

By 1979, a new magnetic reluctance sensor was developed and patented at CSIRO’s Division of Applied Physics, West Lindfield, NSW, leading to Australian Patent 535356 (Pat App PE0925 2-Oct-79) and US Patent 4,439,731. Designed to detect corrosion and damage in high-tension steel cord belts, the instrument became known as the “Conveyor Belt Monitor” or “cbm” [7]. Data from the instrument provided insight not only on belt damage, but on many other mechanical and
operational issues including rubber cover wear measurement [8], vibration including dynamic belt tension monitoring.[9].

Commercial development by CSIRO funded a newly formed “Non-destructive Evaluation and Conveyor Technology Group” led by A. Harrison, providing resources to study the physics and mechanics of conveying systems.

Cbm systems were tested at mines in WA, NSW and Qld, and then in Europe between during the 70s and 80s. The cbm system was licenced by CSIRO to 3 Australian companies; Incor Ltd /cbm Pty Ltd Sydney, Nilsen Electrical Melbourne and McNiece Bendigo. Cbm eventually became the leading and only remaining supplier, resulting in commercial use in mines in Australia, UK, Germany, Asia, South Africa and North America.

Undoubtedly, the development of the cbm system provided a new non-contact measurement tool for belt damage testing as well as for research. The sensor was subsequently used to measure belt flap vibration, rubber cover wear, and dynamic sag (and dynamic tension) during belt starting and stopping, to name a few.

2.2 The University of Newcastle Collaborative Research

As mentioned earlier, collaboration commenced between CSIRO and The University of Newcastle in the early 1980s [10]. Research and collaboration rapidly evolved, coupling the work of both organisations and leading to joint research papers in 1982 on the theory of optimum narrow-high speed belts [11].

Between 1980 and 1984, solutions were derived that describe complex mechanical problems involving dynamic motion of belts. Flexural modes of belt vibration were first measured using multiple distributed cbm sensors for non-contact displacement measurement. Belt flap vibration was mathematically defined using plate mechanics applied to axially tensioned, thick orthotropic plates. Development of new mechanical engineering equations specifying belt-flap vibration frequencies and idler span stabilizing criteria were published.

Research on belt flap vibrations and its control showed that mechanical model optimisations for conveyor design agreed with economic analysis requirements for optimum costing (Roberts et al), namely that narrow high-speed belts were easier to dynamically stabilise at a lowest installed cost.

Ongoing research on elastic wave stress generation in belts during starting and stopping (dynamic analysis) led to the criteria for optimum S-curve starting to minimise dynamic elastic oscillations [12]. In 1984, the 1-st PhD thesis on belt conveying was submitted to an Australian University [13]. In many cases, both flexural (flap) vibrations and elastic vibrations showed non-repeating vibrations and non-linear activity, which later led to the development if chaotic vibration theory for conveyors [14].

3. Examples of Early Milestones in Australian Conveyor Research

Since computing capacity for numerical simulation was limited in the 80s, much of the mathematical modelling and analysis of conveyor dynamics had to rely on mathematical equation derivations. Development of new technology to support conveyor design and operation is broadly reviewed from the author’s perspective in relation to conveyor research in Australia.
Economic Analysis for Conveyor Design Optimisation

The Department of Mechanical Engineering at The University of Newcastle, investigated cost analysis for conveyor design, as well as optimisations for belt handling in the grain and agriculture industries (Roberts, Hayes, Scott et al). Belt width and length were examined in relation to economic and life-cycle requirements [10]. In general, economic analysis including equipment costs and annual equivalent costs per unit length indicated that narrower higher-speed belts were a preferred conveying solution.

Steel Cord Belt Corrosion Monitoring

Removing the possibility of catastrophic belt failure from unobservable steel cable corrosion became an industry-wide issue in the late 70s. March 1979 saw the in-field testing of the magnetic reluctance “cbm” instrument in mines at the Hunter Valley, Pilbara and Alcoa WA. First paper published on the instrument was published in 1979 [7].

Belt Flap Vibration Analysis

Publication of idler-excited belt flap frequencies and dynamic resonance formulas led to design rules for vibration-free operation, and a forerunner to solving the mechanics of narrow high-speed conveyors. A first paper on this topic was published in 1981 [9]:


Dynamic analysis of conveyors, coupled with economic analysis, proved that narrow high-speed conveyors were an optimum mechanical and economic solution. By 1982, the mechanics of transverse belt vibration (Plate Mechanics) was solved for thick composite belts with high bending stiffness [11], allowing design to remove resonances that resulted in belt and structural damage. The equation governing belt flap frequency calculation is shown below.
Flexural Cascades resulting from a Resonant Span

Modes of Vibration of a Vee-return Span

Belts with very large diameter steel cords (> 10 mm) should be analyzed as orthotropic plates. The governing equation of motion is derived by using different values of D in the x and y direction, leading to

\[
D_1 \left[ \frac{\partial^4 w}{\partial x^4} + 2 \frac{D_3}{D_1} \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{D_2}{D_1} \frac{\partial^4 w}{\partial y^4} \right] = -\mu \frac{\partial^2 w}{\partial t^2} + T \frac{\partial^2 w}{\partial x^2}
\]

from which the non-dimensional frequency parameter \( \lambda \) is obtained

\[
\lambda_{mn} = \sqrt{(mn)^4 + 2 \frac{D_3}{D_1} (mn\delta)^2 + \frac{D_2}{D_1} (\delta^4)}
\]  

Equation Defining Belt Flap (Left)

\[
f_{mn} = \frac{1}{2\pi} \sqrt{\frac{D}{\mu} \left( \frac{\lambda_{mn}^2}{\delta} \right) + T \left( \frac{mn}{\delta} \right)^2}
\]

\[
f_i = \frac{v}{\pi d}.
\]

Equation for Modal Frequency (Below)
An optimum spacing of idler supports based on plate mechanics and the governing theory behind belt transverse flap vibration showed that narrow fast belts could be designed without flap resonances, reducing or even removing idler failure and flap-related rolling drag (see figure below).

1982  
[S-curve for Optimal Starting [12]]

Optimal starting and stopping curves were presented at Newcastle in 1982 (Transient Stresses in Long Conveyor Belts, A. Harrison, Proc. Belt Conveying of Bulk Solids, Nov. 1982) [12].

S-curve starting curve theory was developed from principles in “Calculus of Variations” to minimise transient longitudinal belt displacements and dynamic stresses. The method was slowly adopted by industry after 1983. Below are the acceleration conditions for conveyor soft-start equations.

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**Mechanical Criteria**

<table>
<thead>
<tr>
<th>time</th>
<th>vel.</th>
<th>accel</th>
<th>jerk</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 0$</td>
<td>$u_t = 0$</td>
<td>$u_n = 0$</td>
<td>$u_{nn} = 0$</td>
</tr>
<tr>
<td>$t = t_s / 2$</td>
<td>$u_t = \frac{v_b}{2}$</td>
<td>$u_n = a_{max}$</td>
<td>$u_{nn} = 0$</td>
</tr>
<tr>
<td>$t \geq t_s$</td>
<td>$u_t = v_b$</td>
<td>$u_n = 0$</td>
<td>$u_{nn} = 0$</td>
</tr>
</tbody>
</table>

Starting Acceleration S-Curve

$$u_{ts} = \frac{v_b}{t_s} \left(1 - \cos \frac{2\pi t}{t_s}\right)$$  
*is a partial derivative*

Belt Stress

$$\sigma(x,t) = \frac{4E_b}{\pi \nu_b} \cos \frac{\pi x}{L} \left(\int_{0}^{t_s} \left(1 - \cos \frac{2\pi \tau}{t_s}\right) \sin \frac{\pi \nu_t}{L} (t - \tau) d\tau\right)$$

Maximum Dynamic Stress at $Ts/2$

$$\sigma_{max} = \frac{8LE_bv_b}{\pi^2 t_s^2 v_o^2}$$
Elastic wave dynamic analysis was developed using closed-form solutions of the wave equation, resulting in a commercially applicable consulting tool. Critical to the analysis was research that produced the first calculable wave speed in composite belts, where the speed of elastic wave propagation along the carry and return belt sides, $V_c$ and $V_r$ respectively, differ due to mass coupling and friction.

Elastic-wave Strain Variations Due to Boundary Displacement (at the Drive).

Wave-front propagation speed in composite belt materials needed to be determined to properly solve the elastic wave equation for belts in transient states. A dynamic wave model solution was developed. Equations for the wave velocities in empty and loaded belts are shown below [16], where 2 wave equations exist with different solutions. The solution gives rise to a characteristic equation where the roots are not Pi-commensurate. In the below diagrams, “u” is displacement and “v” is velocity.

\[
V_c = V_{cu} - \frac{\Delta Q}{Q_D} (V_{cu} - V_{CL}) \quad (3.18)
\]

\[
V_{CL} = V_{sc} \sqrt{\frac{\mu_{sc}}{\mu + \mu_{IC}(x) + \mu_{m}(x)}} \quad (3.19)
\]

\[
V_{Cu} = V_{sc} \sqrt{\frac{\mu_{sc}}{\mu + \mu_{IC}(x)}} \quad (3.20)
\]

\[
V_{R} = V_{sc} \sqrt{\frac{\mu_{sc}}{\mu + \mu_{IR}(x)}} \quad (3.21)
\]

where $V_{sc} = 4300 \, \text{m/s}$, $\mu_{sc}$ = mass of steel cables (in kilograms per meter), $\mu_{IR}$ and $\mu_{IC}$ are the masses of idlers on the return and carry sides (in kilograms per meter), and $\mu_{m}(x)$ is the mass (in kilograms per meter) of bulk material on the belt. In the preceding discussion, $0.3 < \Delta < 1$, depending on the bulk material [13], and $Q/Q_D$ is the ratio of load on the belt to the design load.
Wave model graphs became the preferred method of demonstrating elastic wave velocities and forces in belts. Graphs were generated by using a solution to the wave equation for elastic belts (symbols have their usual meaning in mechanics):

\[
\begin{align*}
    u_x^C - \frac{1}{V_C^2} u_{tt}^C &= 0, & 0 \leq x \leq L \\
    u_x^R - \frac{1}{V_R^2} u_{tt}^R &= 0, & L \leq x \leq 2L
\end{align*}
\]

Wave Equations for Carry and Return Belt

Roots of the eigen-equation are NOT \( \pi \) Related

\[
\begin{align*}
    \varepsilon \sin \xi \cos \varepsilon + \xi \sin \varepsilon \cos \xi &= 0
\end{align*}
\]

and Mechanical Wave Model of a Belt

1984 (Basic Wave Analysis)

1984

First PhD in Australia on Belt Conveyor Research, Newcastle University [13]

1985

NDT Monitoring Systems for Steel Cord and Fabric Belts (Commercial Developments)

Cable Break Detection - NDT for Steel Cord Belts [15]
Traditionally, the reduction in belt strength and safety factor at a damage site was based on a linear relationship to belt width. However, damage of the axial tensile member in a tensioned belt acts as a stress concentration, resulting in significantly higher strains adjacent to the damage site. Safety factor analysis was researched, and a new stress distribution equation was derived to define a reduction in belt safety factor. Stress is distributed in warp-based composites as shown below.

\[
(T_i - T_{i+1}) = \alpha (T_i - T/n)
\]

Is a non-linear difference equation for \(n\) cables

A solution has the general form

\[
(T_i - T/n) = C_0(n) T e^{-\beta(t-b)}
\]

\[
\beta = -\ln(1-\alpha) = 1.005
\]

Ref. : Harrison, 1987 (22-1) : J. Strain Analysis

A failure Model or Corded Composite Plates with Edge Fractures.

The Mechanical Model

Strain distribution at a damage site

Graph showing the effect on Safety Factor reduction for corded-composite damage (cords or per-unit width warp)

In 2001, research at Newcastle University by Chris Wensrich verified that the above method of analysis is correct for safety factor reduction, by generating a FEA Strand Ver. 6 simulation [17].

The equation used above has been disputed many times by belt suppliers and users that had previously replaced belting based on incorrect assumptions about their failure potential. The research on stress distributions at damage sites in belts provided the justifications for designing conveyors using damage as a factor in component sizing, cost and life expectancy. NDT monitoring was the accepted method for detecting damage in belts.

By the late 80s, funding for mining related research largely derived from consulting and through funded organisations such as TUNRA Bulk Solids, while ACARP, NERDDC and ARC provided grants. The Universities of Newcastle and Wollongong supplied expertise in bulk handling at a level required by Australian companies.
Students undertook research at Newcastle University during the 80s in collaboration with CSIRO research activity. For example, LH Teo was awarded a M.Eng for conveyor research work on idler indentation, belting and bulk material flexural factors using elastic-bed test rigs [19]. Resistance factors were subsequently used to modify existing conveyor design programs.

In 1989, the first university chair in belt conveying was established at Newcastle University. Harrison was appointed Professor of Mechanical Engineering in the university, holding the industry funded Merz-TUNRA Chair in Conveying and Bulk Handling.

A grant allowed the establishment of a Key Centre in Bulk Solids Handling and Particulate Technologies at Newcastle University in 1995. Professor Mark Jones joined the University of Newcastle in 1999, with research in bulk handling and conveying continuing to this day. Considerable research activity followed, with a growth in students in the discipline. During this period, Harrison consulted in the USA and formed Conveyor Technologies Ltd LLC. TUNRA USA Inc, formed in 1993, supported Australian research projects for over 10 years and provided annual conferences and seminars in the USA. TUNRA Bulk Solids formed a joint license agreement with the University of Witwatersrand in South Africa in 2012.

**2000 - Present**

Conveyor-related research in Australia on belt conveying grew considerably in these decades. A total of 8 PhD degrees have been awarded from Newcastle University in belt conveying research (see list in Appendix 1).

A notable increase in student activity occurred after Craig Wheeler was awarded the university’s 2-nd PhD in belt conveying in 2004. The figure below shows a plot of growth in PhD students over the past 36 years at Newcastle University. Consulting and problem solving in bulk handling at TUNRA Bulk Solids fed into the research base in a significant way, and supported research in unsolved conveyor basics, such as indentation and wear/loading issues. PhD degrees in Bulk Handling and conveying total 28 to date (Appendix 1).

With ever increasing computing speeds and programming platforms, simulation and modelling became more accessible to students and researchers. Simulation of bulk material flow used calibrating parameters from a large data base available in TUNRA Bulk Solids. One outcome of current research at Newcastle is the rail conveyor developed by Wheeler. More recent developments in conveying can be expanded upon at another time and venue.
4. Discussion and Concluding Remarks

Subjects researched during the past 20 years are too numerous to cover here, however a short list of achievements might include:

- Conveyor design programs
- Dynamic models and analysis
- Non-linear dynamics and instability analysis (chaos theory)
- Viscoelastic belt dynamics and properties
- Splicing of belts
- Remote NDT damage monitoring and analysis
- Rail systems used for troughed belt conveyor design and patents
- Drive drum friction with viscoelastic considerations
- Conveyor dynamics and drives
- Other conveyor research in pipe-type systems
- Ongoing questions on the variances in indentation rolling losses.

Clearly, the rate of growth in conveyor and bulk handling research has accelerated in recent years. The paper has reviewed only some of the developments in the early years of conveyor-related research subjects in Australia. Future conveyor research is expected to become more environmentally sensitive with regards to dust, water usage and spillage control. Enclosed belt systems may gain popularity, as may off-grid powered conveyors. Enough subject matter exists on belt conveying to facilitate many review papers at future conferences.

5. Appendix 1 : List of PhD Degrees on Belt Conveying, Newcastle University 1984-2019

<table>
<thead>
<tr>
<th>Year</th>
<th>Title</th>
<th>Student</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>PhD Numerical and Experimental Investigation of Dynamic Belt and Bulk Material Interactions in Belt Conveyor Systems</td>
<td>Jiahe Shen</td>
</tr>
<tr>
<td>2017</td>
<td>PhD Three-Dimensional Numerical Modelling of Conveyor Belt Indentation Rolling Resistance</td>
<td>Paul Munzenberger</td>
</tr>
<tr>
<td>2016</td>
<td>PhD Dynamics of Open and Closed Belt Conveyor Systems Incorporating Multiple Drives</td>
<td>Peter Robinson</td>
</tr>
<tr>
<td>2016</td>
<td>PhD A Coupled Model for Material Flexure Resistance in Belt Conveyor Systems</td>
<td>Brian Couch</td>
</tr>
<tr>
<td>2015</td>
<td>PhD Mechanical and Dielectric Relaxation Studies of Conveyor Belt Compounds to Determine Indentation Rolling Resistance Properties</td>
<td>Jane O'Shea</td>
</tr>
<tr>
<td>2013</td>
<td>PhD Bulk Solid Interactions in Belt Conveying Systems</td>
<td>Dusan Ilic</td>
</tr>
<tr>
<td>2004</td>
<td>PhD Analysis of the Main Resistances of Belt Conveyors</td>
<td>Craig Wheeler</td>
</tr>
<tr>
<td>1984</td>
<td>PhD Dynamic Measurement and Analysis of Steel Cord Conveyor Belts</td>
<td>Alex Harrison</td>
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6. References


