عنوان آزمایش :

جذب کننده دینامیکی ارتعاشات

هدف آزمایش :

بررسی و مطالعه چگونگی جذب ارتعاشات در یک سیستم مرتعش با اضافه نمودن یک سیستم فرعی که فرکانش طبیعی آن منطبق بر فرکانس تحریک باشد

تئوری و تجزیه و تحلیل آزمایش :

جذب کننده دینامیکی ، یک سیستم فرعی مکانیکی است که برای کاهش یا از بین بردن ارتعاشات ناخواسته در ماشین ها بکار می رود. این روش بخصوص در ماشین های با دور ثابت که دامنه ارتعاش به علت نزدیکی فرکانس طبیعی آنها به فرکانس تحریک (حالت تشدید) بسیار زیاد گشته و فرکانس نیروی هارمونیک خارجی یا فرکانس طبیعی سیستم هیچکدام قابل تغییر نمی باشد از اهمیت ویژه ای برخوردار است.

اگر به یک سیستم یک درجه آزادی (اصلی) متشکل از جرم m_1 و فنر با ضریب سختی k_1 و نیروی محرک $F=f_0 \sin\omega t$ ، سیستم فرعی متشکل از جرم m_2 و فنر با ضریب سختی k_2 بیافزاییم، سیستم جدید دارای دو درجه آزادی بوده و معادلات تعادل m_1 وm_2 بصورت زیر خواهند بود:

$$m_1\ddot{x}_1 + k_2(x_1 - x_2) + k_1x_1 = f_0 \sin \omega t$$

$$m_2\ddot{x}_2 + k_2(x_2 - x_1) + k_1x_1 = 0$$

که با حل آنها خواهیم داشت :

$$\frac{x_1}{x_0} = \frac{\dfrac{1-\omega^2}{{\omega_{22}}^2}}{\left(1+\mu\beta^2 - \dfrac{\omega^2}{{\omega_{11}}^2}\right)\left(\dfrac{1-\omega^2}{{\omega_{22}}^2}\right) - \mu\beta^2}$$

$$\frac{x_2}{x_0} = \frac{\dfrac{1-\omega^2}{{\omega_{22}}^2}}{\left(1+\mu\beta^2 - \dfrac{\omega^2}{{\omega_{11}}^2}\right)\left(\dfrac{1-\omega^2}{{\omega_{22}}^2}\right) - \mu\beta^2}$$

ω	فرکانس تحریک موتور
${\omega_{11}}^2 = \frac{k_1}{m_1}$	فرکانس تحریک سیستم اصلی به تنهایی
${\omega_{22}}^2 = \frac{k_2}{m_2}$	فرکانس تحریک سیستم فرعی به تنهایی
$\mu = \frac{m_2}{m_1}$	نسبت جرم ها
$\beta = \frac{\omega_{22}}{\omega_{11}}$	نسبت فرکانس ها

از معادلات قبل دیده می شود که به ازای $\omega = \omega_{22}$ ، دامنه نوسان جرم اصلی m_1 یعنی x_1 صفر مشود و بدین ترتیب با انتخاب جرم m_2 یا فنر k_2 به نحوی که $\omega = \omega_{22} = \sqrt{\frac{k_2}{m_2}}$ باشد می توان نیروی وارد به سیستم اصلی را در فرکانس تحریک ω به صفر رساند.

شرح دستگاه و وسائل اندازه گیری :

دستگاه آزمایش مطابق شکل زیر از یک تیر یک سر لولا و یک سر اتصال غلتکی تشکیل شده است که در وسط آن یک موتور با سرعت متغیر نصب گردیده است و همچنین یک دیسک ناهمگن متصل به موتور برای تولید نیروی محرک خارجی هارمونیک وجود دارد. سیستم فرعی جذب کننده متشکل از دو تیغه فولادی و دو وزنه به جرم m می باشد که به فاصله قابل تنظیم l در طرفین تیغه ها بسته می شوند.

در این حالت سیستم فرعی همانند یک تیر یک سر گیردار مرتعش عمل می کند و فرکانس آن بدین صورت است:

$$f = \frac{60}{2\pi}\sqrt{\frac{3 * E * I}{l^3(m + 0.236\, m_0)}}$$

$E=210\ Gpa$	مدول الاستیک تیغه ها
$2m_0 = 106.5\ gr$	جرم دو تیغه از جنس فولاد معمولی
$m = 143\ gr$	جرم هر کدام از وزنه های جاذب ارتعاش
f	فرکانس طبیعی سیستم فرعی بر حسب rpm
I	ممان سطح تسمه فنری جاذب ارتعاش
l	فاصله هر یک از جرم ها تا تکیه گاه

روش انجام آزمایش :

در حالی که جاذب به سیستم متصل نیست ، دستگاه کنترل سرعت را روشن کرده و با چرخاندن کلید، سرعت موتور را به تدریج زیاد کرده تا دستگاه به دور بحرانی خود برسد. در این حالت دور موتور را یادداشت می کنیم.

بدون اینکه دستگاه را خاموش کرده یا سرعت را تغییر دهیم، جاذب ارتعاشات را در زیر موتور و در محل مخصوص نصب کرده و سپس دو جرم فرعی را به طور همزمان و به فاصله یکسان از هم قرار داده و جابجا می کنیم تا حداکثر ارتعاش سیستم اصلی از بین برود. در این صورت فاصله جرم سیستم فرعی (مرکز جرم تا ابتدای تسمه) را اندازه گیری می کنیم.

خواسته های آزمایش :

۱- فرکانس طبیعی f_n را از فرمول بدست آورده و با مقدار تجربی آن مقایسه کنید و درصد خطا را بدست آورید.

۲- معادلات حاکم بر ارتعاش سیستم دو درجه آزادی را بدست آورید.

۳-چند نمونه از موارد استفاده جاذب دینامیکی ارتعاشات نام ببرید.

1

$l = 105 * 10^{-3} \quad m$

$E_{steel} = 210 * 10^{9} \quad pa$

$I = 2I' = 2 * \frac{1}{12} * (12 * 10^{-3}) * (2 * 10^{-3})^{3} = 1.6 * 10^{-11} \quad m^{4}$

$2\ mass\ of\ vibration\ catchy \quad \rightarrow \quad m = 2 * m' = 2 * 143 * 10^{-3}\ kg$

$mass\ of\ dinamic\ vibration\ catchy \quad \rightarrow \quad 2m_0 = 106.5 * 10^{-3}\ kg$

فرکانس طبیعی تئوری طبق فرمول برابر است با :

$theory\ natural\ frequency:$

$$f_{n_1} = \frac{60}{2\pi}\sqrt{\frac{3*(210*10^{9})*(1.6*10^{-11})}{[(2*143*10^{-3})+(0.236*106.5*10^{-3})]*[105*10^{-3}]}} = 1597 \quad rpm$$

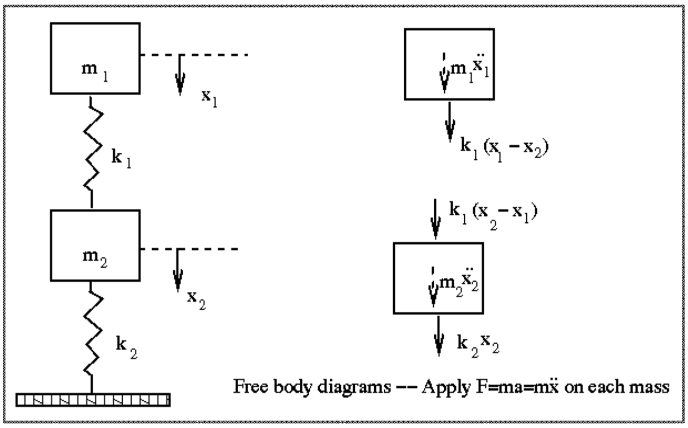
فرکانس طبیعی تجربی از آزمایش داریم:

$tentative\ natural\ frequency:$

$f_{n_2} = 1150 \quad rpm$

درصد خطا :

$$\Delta_{f_n} = \frac{|f_{n_2} - f_{n_1}|}{f_{n_2}} * 100 = \frac{|1150-1597|}{1150} * 100 = 38.87\ \%$$



$$m_1\ddot{x}_1 + k_1(x_1 - x_2) = 0$$

$$m_2\ddot{x}_2 + k_1(x_2 - x_1) + k_2x_2 = 0$$

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{pmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$if\ let\ \begin{cases} x_1 = a_1 \sin \omega t \\ x_2 = a_2 \sin \omega t \end{cases} \quad \rightarrow \quad \begin{cases} \ddot{x}_1 = -a_1\omega^2\ \sin \omega t \\ \ddot{x}_2 = -a_2\omega^2 \sin \omega t \end{cases}$$

عبارات بدست آمده را در معادلات به فرم ماتریسی قرار می دهیم:

$$\begin{bmatrix} k_1 - m_1\omega^2 & -k_1 \\ -k_1 & (k_1 + k_2) - m_2\omega^2 \end{bmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = 0$$

$$\det\begin{bmatrix} k_1 - m_1\omega^2 & -k_1 \\ -k_1 & (k_1 + k_2) - m_2\omega^2 \end{bmatrix} = 0 \quad \xrightarrow{\omega^2=\lambda} \quad (k_1 - m_1\lambda)(k_1 + k_2 - m_2\lambda) - {k_1}^2 = 0$$

معادلات فوق را بر اساس λ حل می کنیم پس از حل آن و بدست آوردن ω میتوانیم جواب های x_1 و x_2 را بدست آوریم.

از کاربردهای جاذب مکانیکی ارتعاشات می توان به موارد زیر اشاره کرد:

جذب ارتعاشات پل های کابلی با استفاده از دمپرها:

Vortex excitation of an isolated cable or groups of cables

جلوگیری از بوجود آمدن امواج گردابه ای در یک کابل و یا مجموعه کابل ها

Rain/wind-induced vibrations of cables

جذب ارتعاشات بوجود آمده توسط باد و طوفان در کابلها (کابهای دکل برق و یا پل های کابلی)

Galloping of single cables inclined to the wind

جلوگیری از خم و راست شدن کابل ها و برخورد انها به هم

Motions caused by fluctuating cable tensions

جذب ارتعاشات ناشی از حرکات موجی و کششی کابل ها

نمونه ای از این جاذب ها را میتوان در پایه تکیه گاه های پل های کابلی مشاهده کرد

اما دسته ای دیگر از این نمونه جاذب ها را میتوان جاذب دینامیکی ارتعاشات نامید که یکی از کاربردهای آن برای جذب ارتعاشات خطوط انتقال برق می باشد. به این دسته از جاذب ها **Haro Damper** و **Dogbone Damper** می نامند که شرح کامل آن در گزارش ضمیمه شده است.

نتیجه گیری :

در این آزمایش متوجه شدیم که موتوری که روی تیر نصب شده است و نیروی هارمونیک اجباری برای یک سیستم دو درجه آزادی ایجاد میکند ، با تنظیم فرکانس طبیعی سیستم فرعی دوم که همانند سیستم اول ولی در مد مخالف حرکت میکند، میتوانیم نیروی هارمونیک فرعی ایجاد کنیم که فرکانس آن با فرکانس طبیعی ارتعاش تیر برابر شود و ارتعاشات را جذب و خنثی کند و باعث فاصله گرفتن فرکانس طبیعی از فرکانس تحریک و بوجود نیامدن حالت تشدید می شود. این سیستم جاذب دینامیکی ارتعاشات نام دارد

توجه داشته باشیم که این سیستم جدا از یک سیستم جرم – فنر با دمپر هست و میتوان با دو درجه آزادی کردن یک سیستم SDOF ارتعاشات ناخواسته آن را جذب و خنثی کرد.

همچنین با توجه به

$$f = \frac{60}{2\pi}\sqrt{\frac{3 * E * I}{l^3(m + 0.236\, m_0)}}$$

میتوان دریافت که با تنظیم دقیق فاصله جرم ها از تکیه گاه تیغه ها میتوان فرکانس فرعی را با خطای کمتری نسبت به فرکانس طبیعی تیر تنظیم نمود.

ضمائم :

بخشی از مقاله ای در باره جاذب دینامیکی ارتعاشات و کاربرد آن در خطوط انتقال برق بصورت لاتین ضمیمه شده است

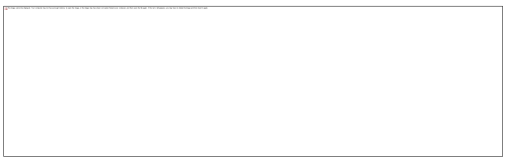
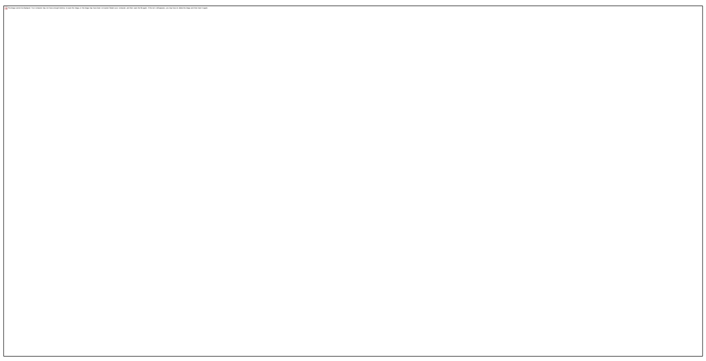
After 1962 first "Zenith" and then "Ontario Hydro" recorders were introduced and installed on lines in Victoria and South Australia.

An attempt to provide damping at higher frequencies which were being recorded on many lines across flat open country in South Australia was made by Dulmison who developed the ES-1 Stockbridge. This was, in effect, a standard stockbridge damper with an elastomer sandwich between the 7 strand messenger cable and the weights - an attempt to use viscous damping at the higher frequencies. At this time it was the practise to make "Stockbridge" dampers (actually Monroe and Templin dampers) with 7 strand messenger cable similar to that used in earth wire or guy wire. This was of 90 ton (1400 mPa) grade and heavily galvanised.

As the messenger strand weathered or became polluted by dust and other contaminants entering its open strand lay, it was thought that its performance as a coulomb damper would be affected. Following English and European practice of the time the messenger strand was heavily greased and then covered by a protective sleeve of flexible conduit with the intention of making it weatherproof and long lasting.

The vulcanised neoprene covering provided in the ES-1 design served this same purpose so that the performance of the damper was expected to be consistent throughout its service life.

Unfortunately, the damping properties were responsive to frequencies far above the range caused by aeolian vibration and they proved to be less effective in the critical frequency range. Most of the ES-1 dampers suffered from the weights falling off the end of the neoprene covered messenger cable (Figure 12).

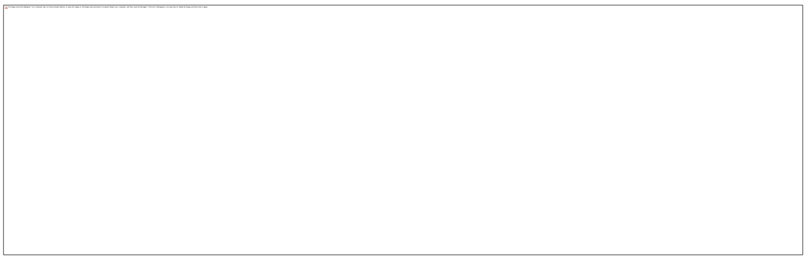
Elastomer Sandwich (ES-1)

Figure 12

Because of these failures the weight pull-off test was introduced into the Australian Standard 1154/1.

At the same time, because of conductor fatigue failures at the stockbridge damper attachment points, another attempt was made to improve the clamping mechanism, which was in effect, addressing the symptom and not the cause.

The attachment clamp was lined with a heavy coating of elastomer and clamped on to the conductor using helical rods. This "improvement" was called the ES-2 (Figure 13).



Elastomer Sandwich (ES-2)

Figure 13

Whilst the ES-2 solved the problem of fatigue damage to the conductor at the damper attachment point the effect of the elastomer sandwich was to inhibit the transfer of energy from the vibrating conductor to the messenger cable at the appropriate frequencies and to exhibit viscous damping properties at frequencies beyond the range experienced.

The ES-2 did not absorb enough energy at the frequencies recorded and although the damper caused no fatigue to the conductor at the attachment point it did not dampen the vibration at the most damaging frequencies.

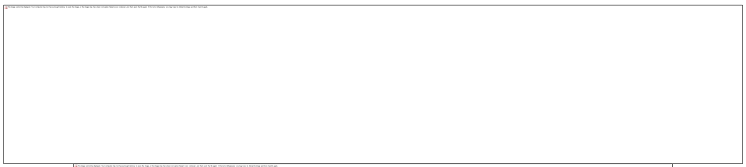
Many conductor fatigue failures from varying types of vibration dampers were experienced at the attachment points of the vibration dampers which were reported to CIGRE in 1971 - Ref 3.

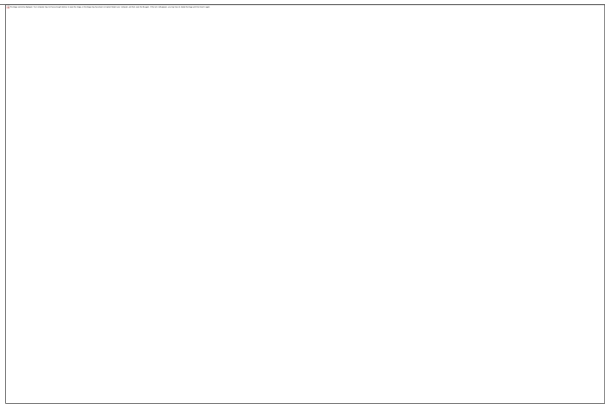
It was realised that the energy from a vibrating conductor had to be transferred directly into the messenger cable so that it could be absorbed by hysteresis and interstrand friction and then dissipated into the air in the form of heat.

The solution it was thought, was to have a conventional stockbridge type damper but with more than 2 degrees of freedom and a more energy absorbing type of messenger cable.

Because of unsolvable problems with vibration in Saskatchewan in Canada, a consultancy programme was commenced in Finland, where a disused railway tunnel allowed full span experiments to be conducted without the influence of ambient wind and temperature variations. - Ref 4.

In 1970 Lauri Haro of Imatran Voima and Tapani Seppa devised a "stockbridge" damper with three weights, suspended from two clamps attaching it to the conductor. The weights were of varying dimensions and at different moment arms on the messenger cable. Each of the two main weights had two degrees of freedom as in a normal stockbridge damper - but at different and overlapping frequencies. The weight on the short arm responded to frequencies higher than that on the longer arm (Figure 14).



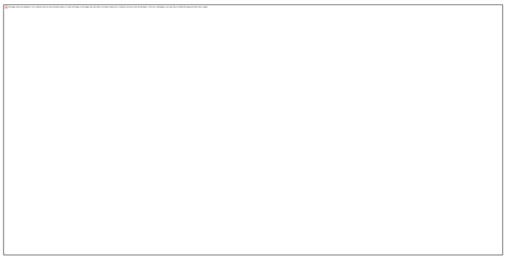


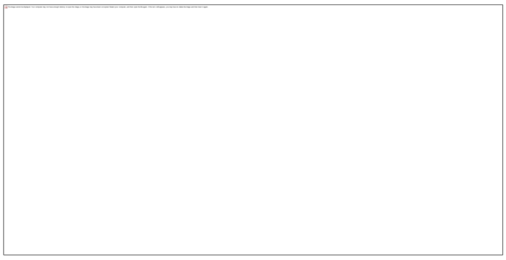
Haro Damper

Figure 14 and Photo

The Haro damper, although expensive, virtually solved the vibration problems at Saskatchewan Power. Its one disadvantage was that it was over a metre in length and was difficult to transport and install - many became bent and damaged in transit. Dulmison obtained the license to manufacture Haro dampers and sold many thousands to the Canadian utilities but very few in Australia.

Dulmison produced the VARISPOND damper in 1975 which employed two equal weights with moveable doughnut shaped attachments which could be positioned at different stations on the main weight. This changed the centre of gravity of each weight so that one side of the damper could be tuned to a higher frequency than the other. The theory was that any damper could be "tuned" to the required ranges of frequencies depending on vibration frequencies actually being recorded on the line. It was found from experience that certain fixed settings of the moveable donuts performed best so that frequency response, whilst broadened, was no longer variable (Figures 15 ,16).



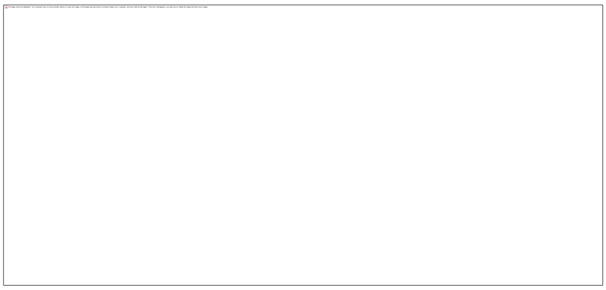


Varispond Damper

Figures 15 ,16

A stockbridge type damper with 3 degrees of freedom was invented by Dulmison in 1976. This employed the two conventional modes of the stockbridge (bending of the messenger cable in the vertical plane) but added a torsional mode by offsetting the weight from the vertical plane.

The original proposal was to provide a weight shape which could be made cheaply so that internal cores and the manufacturing problems with galvanising the inside of the cylindrical shaped weights could be eliminated. Experiments were conducted with the top half of cylindrical weights cut off and welded to the bottom section so that the centre of gravity of the weights would remain the same (Figure 17).

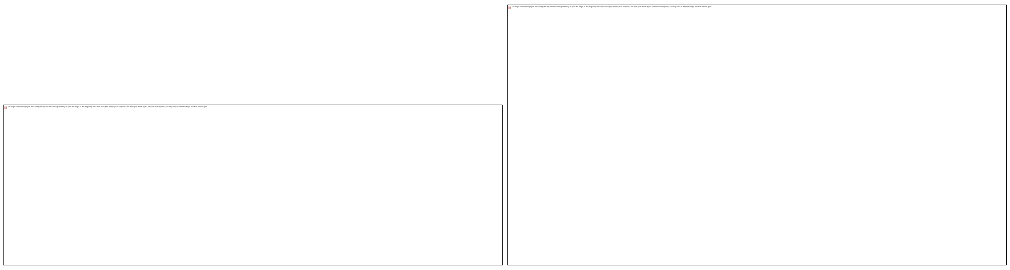


Dogbone Damper Prototype

Figure 17

If the weights were then rotated 90 degrees so that all mass was on one side, it would impart a torsional movement to the messenger at the same time as the two vertical modes of bending.

With experimentation the weight shape was refined until what we now know as the DOGBONE was developed (Figure 18).



Dogbone Damper

Figure 18 and photo

Whilst the DOGBONE damper did not have the same coverage of frequencies as the HARO damper nor the VARISPOND damper it was very simple and inexpensive to manufacture and became very popular in most parts of the globe.

About the same time as the DOGBONE damper was developed in Australia, the University of Milano driven by Drs Diana and Falco and Dr Claren of SALVI developed a HARO type damper on simpler lines. They used two weights instead of the complicated three weights of the HARO damper and opened up the cylindrical weights into an open clothes peg design, thus making them cheaper to produce (Figure 19).

Salvi 4R Damper

Figure 19

At the same time, they recognised the importance of the messenger cable which had to dissipate all the wind energy imparted to the conductor at all the frequencies experienced. They developed a 19 strand cable instead of the earlier 7 strand dampers and wound it tightly in short pitches around a central king wire. To be effective the strands were made of preformed wires and then post-formed so that they were tightly embedded against each other.

The earlier problems of clamping stresses at damper attachment points was finally overcome, not by developing a better clamp (for there had never really been anything wrong with the attachment method) but by satisfactorily controlling and damping the conductor vibration at all frequencies. With the amplitude of vibration reduced to very low levels there are virtually no dynamic stresses either at the suspension clamp or the damper clamp. SALVI'S 4R damper utilised a flat sided hexagonal clamp so that a large range of conductor sizes can be accommodated (Figure 20).

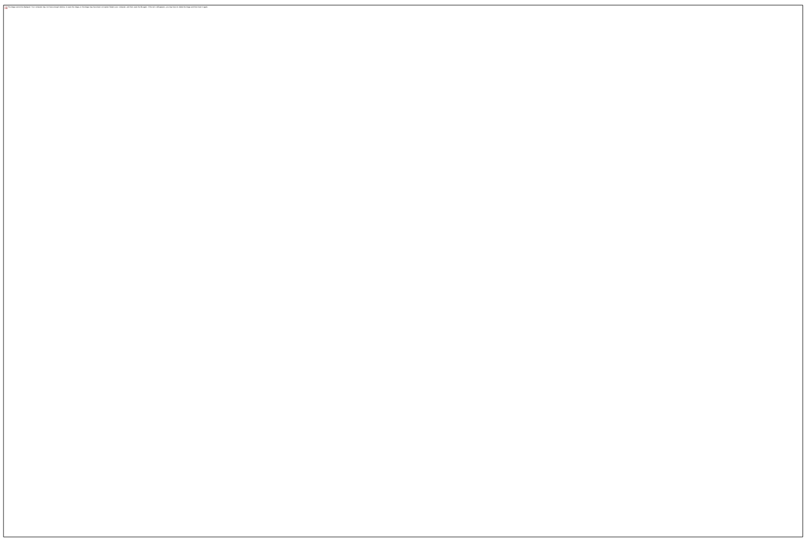
Salvi hexagonal clamp

Figure 20

Other European and American manufacturers adopted the HARO/SALVI principle.

From computer programmes and experiments the frequency responses were designed, for the first time, to cover the full spectrum experienced from aeolian vibration.

Although widely used all over the world and made by Italian, German, Austrian, French and American manufacturers, this multi-resonant damper was not used in Australia to any extent until 1994 when Dulhunty Industries started to produce the 4D series. It is now used in considerable numbers in every state of Australia (Figure 21 - Photo).



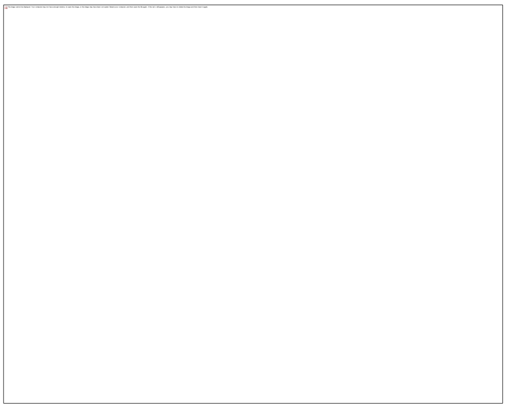
Dulhunty 4D Vibration Damper

Fig 21 photo

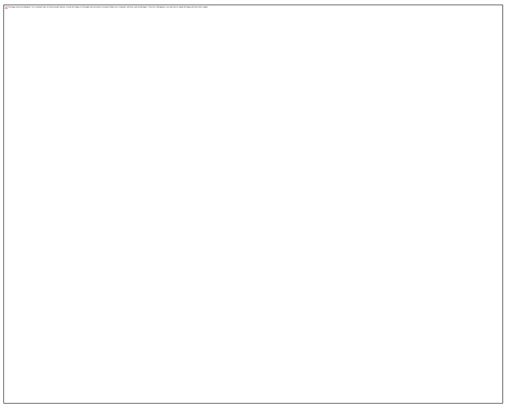
With the ever-increasing use of AAAC1120 alloy conductors in Australia replacing conventional ACSR on transmission lines the need for a highly efficient energy absorbing damper with a wide range of frequency response has become vital. Not only is this conductor more prone to vibration because its mass per unit length is so much lower, but because its self damping properties have been shown to be considerably less than equivalent ACSR.

Independent investigation and testing of the Dulhunty 4D series dampers on AAAC1120 alloy by the Georgia Power Research Laboratories in Atlanta has demonstrated the remarkably wide range of frequency response and high level of efficiency of this latest family of vibration dampers (Figures 22 and 23).

Typical Dulhunty 4D Damper Efficiency (ISWR) Curves



4D-20 Damper on "KRYPTON" AAAC
(16.25dia)
Figure 22



4D-40M Damper on "SULPHUR" AAAC
(33.75dia)
Figure 23