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# MECHANICAL ENERGY MANAGEMENT FOR SEMI-ACTIVE DAMPING OF IMPACT BORNE VIBRATIONS

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**Summary:** *This paper presents a prototype of so called PAR node, i.e. a semi-active structural joint capable of switching its state between frame and truss mode. If installed in a frame structure such a joint can be used to introduce a control force which opposes the oscillatory movement initiated at impact or other sources for free vibration, without a considerable additional energy sources. The control force is applied using as energy source either strain or kinetic energy of the vibrating structure itself, thus the method is considered semi-active. Consequently presented joints can be used in connection with so called Prestress Accumulation Release (PAR) strategy to manage conversion of portions of mechanical energy from strain energy to kinetic energy of higher modes of vibration which is then effectively dissipated.*

## 1. INTRODUCTION

Some engineering structures are exposed to transient dynamic loading which, although not dangerous for the structure itself, may generate harmful or undesirable effects. It has been therefore an engineering problem to eliminate vibrations induced by non-destructive impacts, force impulses generated by working machinery, etc. Effective mitigation of such vibration might for example help improve the resolution of optical equipment or reduce the noise generated by vibrating structure. Out of three classes of possible solutions, i.e. passive, active and semi-active, there has been a growing attention to the semi-active methods which allow for adjusting some mechanical parameter characteristic on one hand, and utilise the structural deformation to introduce control forces – on the other hand. One advantage of the latter feature, which is common with passive devices, is that the system does not require external power to directly generate the control forces. The external power is needed to regulate an actuator which in turn changes the magnitude of the control force according to the control unit algorithm and is typically in the order of magnitude of tens of Watts. Symans and Constantinou in [1] give definitions of all three classes of methods and provide a review of semi-active solutions for seismic protection of structures. In particular a reference is given to a stiffness control device introduced by Kobori et al. [2], where bracing of a frame structure is locked or unlocked in order to keep the structural response at lowest possible level during an earthquake. Also, the design assures that in the power failure situation the structure works with maximum stiffness, i.e. with the bracing locked.

Another group of techniques which gained attention especially in seismic engineering is utilisation of semi-active friction dampers for energy dissipation. Such dampers can be installed either within a structure as part of additional bracing [3] i [4], or as adaptive stiffeners between adjacent structures [5] i [6]. In either case the slip condition and the friction generating contact force can be controlled with a piezoelectric actuator. A similar approach has been adopted in the present study.

Among many available concepts of tailoring semi-active techniques to mitigate vibration, synchronised switch damping (SSD) techniques generate voltage magnification and a phase shift between the mechanical strain and the resulting voltage of a piezoelectric element. As a result a force always opposite to the velocity is obtained and the level of dissipation corresponds to the part of mechanical energy converted into electric energy. A review of SSD and other semi-active techniques utilising piezoelectric elements is given in [7]. Another interesting example of coupling structural response with PZT actuators is given in work [8].

Design of adaptive structures for improved load capacity has been proposed in [9], while semi-active approach to reducing impact load intensity via plastic-like yielding "structural fuses" has been analyzed in [10].

Technical application of adaptive shock-absorbers to adaptive landing gears and vehicle suspension is discussed respectively in [11] and [12]. Other semi-active technical solutions for mitigation of impact loads are presented in [13], [14] and [15]. The concept described in [16] deals with the use of on-off rod connections control for energy dissipation in a flexible truss-beam structure, whereas in [17] a concept is proposed for vibrations suppression in a mass-spring system due to a controlled detaching and reattaching of a spring.

In the present work a prototype of a semi-active structural joint is presented, which allows for implementation of so-called Prestress Accumulation Release (PAR) technique which aims at mitigation of free vibrations. In up-to-date publications the efficiency of the PAR strategy has been shown numerically for layered structures [20] and for frame structures [21]. In either case the PAR strategy aims at conversion of portions of mechanical energy from strain energy to kinetic energy of higher modes of vibration which is then effectively dissipated. With PAR nodes installed in the structural joints of a frame structure the mechanical energy management can be attempted, i.e. conversion of portions of mechanical energy as described above, and consequently a very effective method for damping of fundamental mode of vibrations can be implemented.

## 2. PAR STRATEGY FOR FRAME STRUCTURES

In the PAR strategy it is assumed that a structure undergoes free vibrations and that there is a certain device or devices installed in the structure capable of imposing kinematic constraints on some degrees of freedom of the system. For instance, a layered beam could be equipped with a device that allows or constrains the relative slip between layers, or a system composed of masses and springs is equipped with a device which releases or reattaches a chosen spring to a mass. Given such devices are in place, the strain accumulated in the structure could locally be released which results in conversion of a part of the strain energy to the kinetic energy of local, higher frequency vibrations. In the next phase constraints are reimposed which results in ”freezing” of a part of the deformation. Local, higher frequency vibrations introduced after reimposing of the constraints can be effectively damped out with material damping. An interesting example of a passive TMD device for damping portions of kinetic energy locally in order to achieve global mitigation effect is described in [18].

If the time instant of reimposing constraints is chosen properly, i.e. at the moment of maximum relative dislocation between top and bottom beam, it will introduce a prestress in the structure. It should be emphasised at this point that a relatively small energy was used to adjust the actuator device, f.e. a piezo actuator that controls the friction in a joint (like one introduced by Gaul [19]) and in turn a control force was generated in the structure that is a result of the structural motion itself. Furthermore the generated prestress acts in the direction that opposes the movement of the structure. As mentioned in [1] such a behaviour is desirable for many semi-active techniques because it promotes the stability of the system. Obtained prestressed structure, with a new equilibrium configuration, could then return to the initial state by means of a gradual, quasi-static release of the prestress accompanied by the frictional dissipation in the contact surfaces. For many practical cases the above procedure needs to be repeated until the desired effect is obtained. As a result a very high potential in the mitigation of the fundamental mode of vibrations is achieved.

The goal for this work is to introduce the first order prototype of a PAR node in the form of a semi-active, conical, frictional assembly actuated with piezoelectric stacks.

## 3. PAR NODE

A PAR node presented in this section is a first prototype of such a device manufactured for demonstrative purposes. Assumptions for the device were the following:

- in the frame mode it should be able to sustain internal moments corresponding to the assumed load regime of the whole demonstrator structure,
- moment bearing capability of the node should be realized via frictional surfaces,
- in passive operation (no control signal) a pre-stressed, elastic element should apply the friction generating normal force into the interface,
- in the passive operation (no control signal) the node should stay in the frame mode with maximum stiffness,
- the actuator should be able to apply enough maximum force to completely cancel the friction generating normal force introduced by the elastic element.

### 3.1 Actuator

Various possibilities have been considered for the actuator, including electromagnetic coupling, magnetostrictive rods and piezoelectric actuators. The only technology, which offered enough force with small stroke and small mass was a parallel pre-stressed piezoactuator.
Based on the calculations and simulations carried out for the proposed demonstrator, it has been assumed that the PAR node in the frame mode should carry bending moments up to 20 Nm. Corresponding value of ca. 2950 N of maximum generated force can be obtained with Cedrat Technologies parallel pre-stressed piezoactuator PPA40L (cf. Fig. 1). The actuator characteristic is the following:

$$F_{act} = -\left(\frac{u}{u_{max}}\right) F_B + \left(\frac{V}{V_{max}}\right) F_B, \tag{1}$$

where:
$F_{act}$ - actuator force
$F_B$ - max. force generated with the actuator
$u_{max}$ - max. actuator stroke
$u$ - actuator stroke
$V$ - applied voltage
$V_{max}$ - max. allowable voltage.

The above characteristic for PPA40L is depicted in Fig. 2. Because of the visible trade-off between the generated stroke and generated force, minimum possible clearance between the actuator and the casing is required during actuator assembly.

Figure 1. Cedrat Technologies parallel pre-stressed piezoactuator PPA40L.

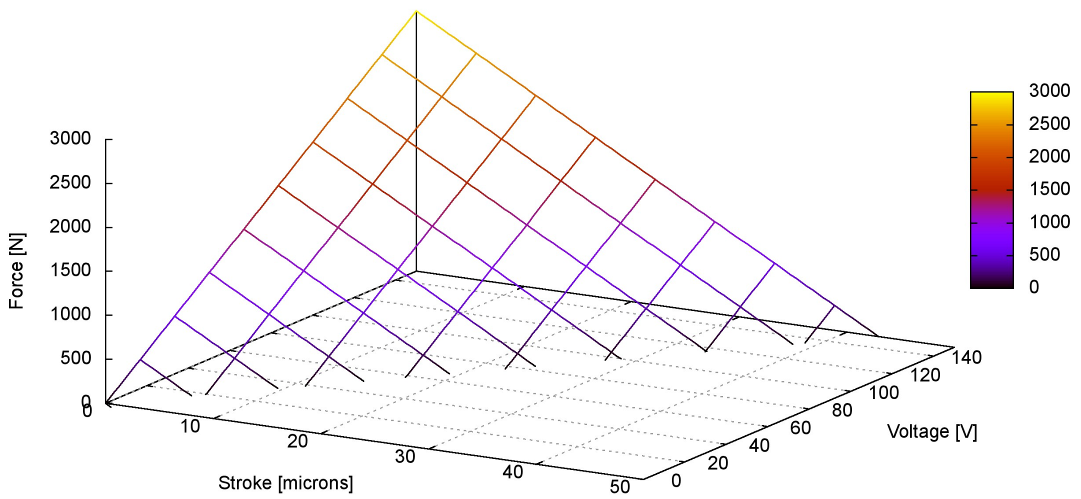


Figure 2. Characteristic of the PPA40L actuator.

### 3.2 Conical fit assembly

Assuming that $M_f$ is the maximum moment in the connection, the slip condition takes the form:

$$M_f - \mu\, F_n\, 0.5\, dm < 0, \tag{2}$$

where:

$\mu$ - friction coefficient
$F_n$ - normal force generated on contact surfaces
$dm$ - medium cone diameter.

In a simple key assembly shown in Fig. 4 the normal force transferred through the contact surfaces exceeds the axial force applied to the connection, according to the formula:

$$F_n\,(F_a) = F_a\, k_a = \frac{F_a}{\sin\left(\dfrac{\alpha}{2}\right) + \mu\, \cos\left(\dfrac{\alpha}{2}\right)}. \tag{3}$$

For example, taking the friction coefficient $\mu = 0.1$ and the cone angle $\alpha/2 = 10\,\mathrm{deg}$, $k_a$ equals $3.67$. If the spring force is equal to $75\%$ of the maximum force generated by the actuator PPA40L, i.e. $Fa = 0.75\, F_B = 2225\, N$ then the maximum moment transferred by the connection is $23.4\, Nm$. Values of $M_f$ as a function of cone angle and the cone diameter are depicted in Fig. 3.

In general $M_f$ increases linearly with the cone diameter and non-linearly with the decrease of the cone angle. Taking into account geometrical and mass constraints, the cone diameter

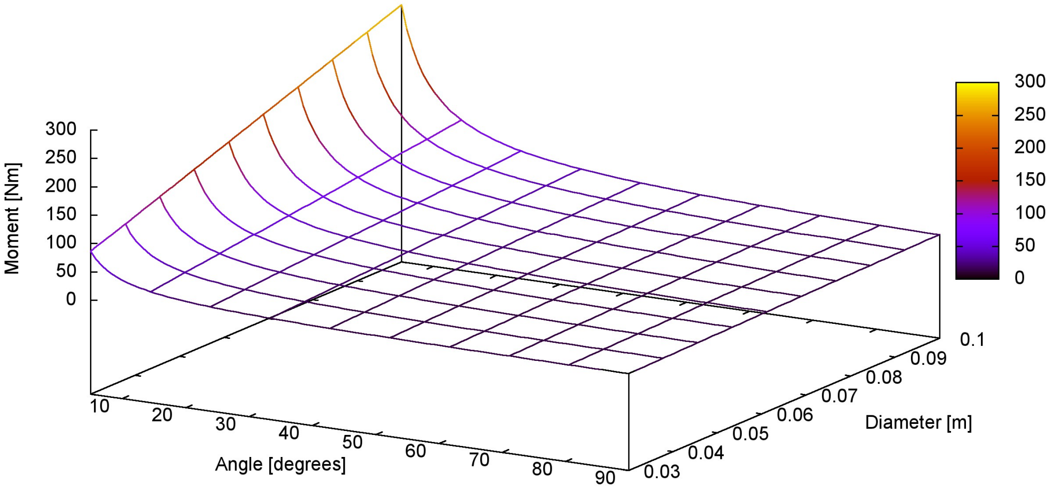


Figure 3. Characteristic of the conical fit assembly.

has been chosen to 6 cm. Minimum cone angle is constrained with condition preventing the harmful effect of self-blocking described in [22], which might occur during disconnecting of the frictional surfaces:

$$\alpha > 2\ \arctan\left(\mu\right)\ k_s, \tag{4}$$

where $k_s$ is an additional safety factor. Minimum cone angles corresponding to various friction coefficients, with assumed $k_s = 1.3$ are shown in Tab. 1.

Main dimensions of the PAR node are summarized in Tab.2 and the general view is shown in Fig. 4a). During normal operation the prestressed elastic element introduces the pressure applied to the contact surfaces. It should be noted that this state of maximum moment bearing capability is active also in case of power break down, or when the control system is turned off. The transition into the truss mode is obtained via application of the actuator force that

| $\mu$ | $\alpha_{min}\ [degrees]$ |
|---|---|
| 0.01 | 1.5 |
| 0.05 | 7.4 |
| 0.1 | 14.8 |
| 0.2 | 29.4 |
| 0.3 | 43.4 |
| 0.4 | 56.7 |

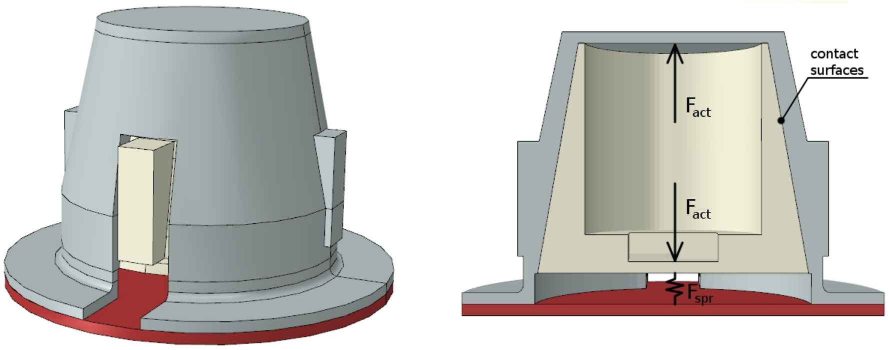
Table 1. Minimum cone angles preventing the self-blocking phenomenon.

counteracts the force generated with the prestressed element, cf. Fig. 4b).

A numerical model of the assumed geometry has been build and the ability of the connection to bear the applied moment has been tested. Assumed model included a steel-to-steel hard contact with friction coefficient of $0.1$ and a pre-stressed elastic element generating the force equal to $2225\,N$. Boundary conditions included clamping of the two connecting rods while the third connecting rod has been loaded with moment generating lateral force.

| Parameter | Value |
|---|---|
| center diameter of the conical surface | $60\,mm$ |
| cone angle | $20\,degrees$ |
| casing external dimensions (base diameter x height) | $110$ x $78\,mm$ |
| PPA 40L actuator external dimensions | $57$ x $23.5$ x $18\,mm$ |

Table 2. Main dimentions of the PAR node.



a) b)

Figure 4. PAR node assembly: a)general view; b) cross section.

Figure 5 shows the relative rotation between two adjacent frictional surfaces as a function of moment applied in the connection. At low values of the applied moment, sticking contact surfaces rotate together under elastic deformation. The threshold value of $24.1\,Nm$, at which slip initiates is clearly visible. This value corresponds well with the estimation of $24.5\,Nm$ obtained with eq. 2 with no safety factor. It can be thus concluded that the PAR node in the frame mode is able to transfer moments up to ca. $24\,Nm$.

In the second stage the model has been additionally loaded with an increasing actuator force counteracting the pre-stressed spring force. It can be observed in Fig. 6 that initially loaded and sticking contact surfaces begin to slip as the sum of elastic element and actuator forces decrease. At $23.0\,Nm$ and the applied actuator force of ca. $950\,N$ the contact surfaces rotate almost freely with respect to each other and so the connection has almost no moment bearing capability. At $10.0\,Nm$ the connection still offers some resistance to the applied moment at the actuator force of $1600\,N$. These values are higher than values obtained with the formula 2 which estimate the slip at $150\,N$ and $1300\,N$. The reason for this could be due to the fact,

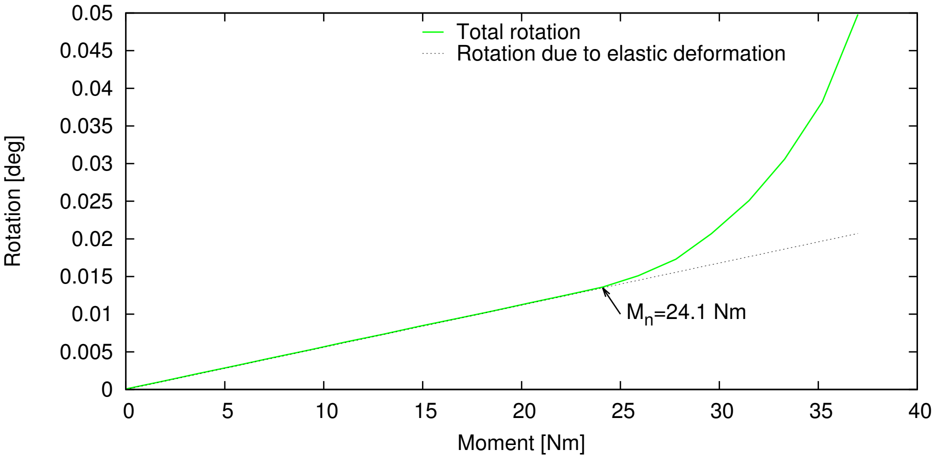


Figure 5. Maximum applied moment before slip.

that the formula refers to an ideal case, whereas in more detailed model the slip regions initiate locally and increase gradually, which corresponds to a transition zone between ultimate stick and slip states for which static equilibrium can still be found.

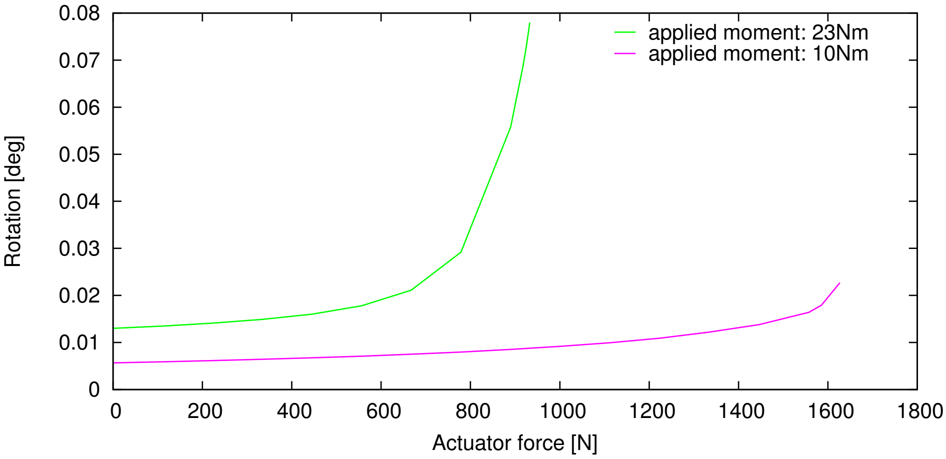


Figure 6. Slip between contact surfaces at chosen values of the applied moment at increasing actuator force.

### 3.3 Frame structure

For demonstration of the efficiency of the PAR strategy in frame structures for mitigation of the fundamental mode of vibration, semi-active nodes described in section 3.2 were installed in an example frame structure. The general view of the assumed demonstrator is shown in Fig. 7. All elements are made of steel with the total mass of the structure equal to $6.1\,kg$ and the mass of an active node equal to $0.8\,kg$. Mode shapes were extracted twice for the demonstrator struc-

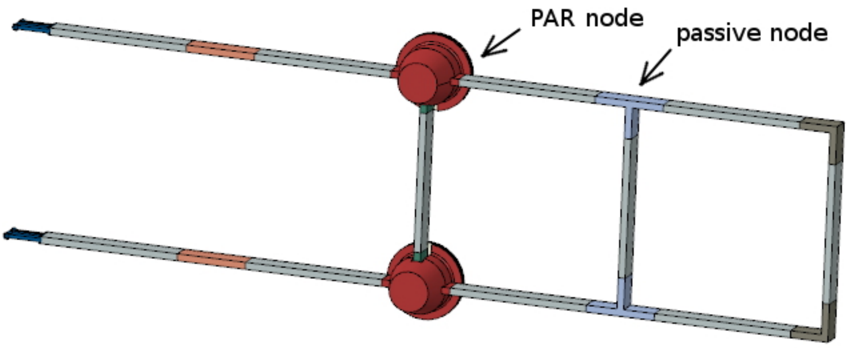


Figure 7. General view of the assumed demonstrator frame structure with semi-active nodes.

ture using a simple beam model, i.e. for the frame and truss state of semi-active nodes. Chosen mode shape and eigen frequency comparison for two states of semi-active nodes is shown in Fig. 8 - 11 and in Tab. 3.3, where $\omega_f$ refers to frame mode eigen frequency and $\omega_t$ refers to truss mode eigen frequency.

As can be seen in Tab. 3.3, the fundamental eigen frequency corresponding to truss and

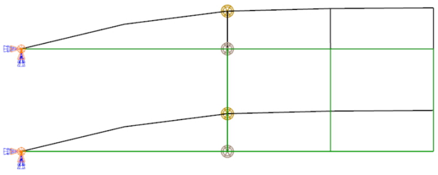


Figure 8. Mode shape No 1: $\omega_f = 6.74\,Hz$, $\omega_t = 4.34\,Hz$.

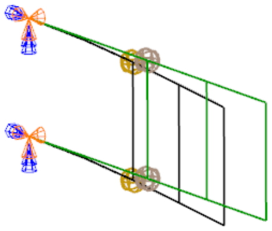


Figure 9. Mode shape No 2: $\omega_f = 13.42\,Hz$, $\omega_t = 13.42\,Hz$.

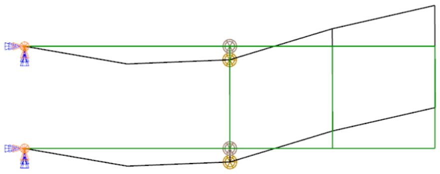


Figure 10. Mode shape No 5: $\omega_f = 54.80\,Hz$, $\omega_t = 45.50\,Hz$.

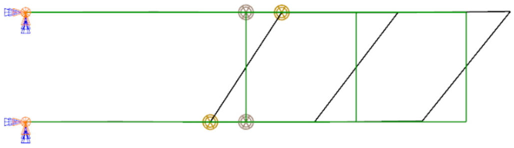


Figure 11. Mode shape No 21: $\omega_f = 756.1\,Hz$, $\omega_t = 756.0\,Hz$.

| Mode shape No | Description | $\omega_f\,[Hz]$ | $\omega_t\,[Hz]$ |
|---|---|---|---|
| 1 | $1^{st}$ in-plane bending | $6.74$ | $4.34$ |
| 2 | $1^{st}$ out-of-plane bending | $13.42$ | $13.42$ |
| 5 | $2^{nd}$ in-plane bending | $54.80$ | $45.50$ |
| 21 | $1^{st}$ longitudinal, antisymmetric | $756.1$ | $756.0$ |

Table 3. Eigen frequencies of the demonstrator structure in frame ($\omega_f$) and truss($\omega_t$) modes.

frame state of semi-active nodes differs by ca. $55\%$. Based on the gained experience it can be concluded that this is sufficient for mitigation of the fundamental frequency using the PAR strategy. Furthermore, the first bending mode in the out-of-plane direction is well separated from the other modes and hence this mode should not be excited with the initial in-plane displacement.

Eigen mode corresponding to longitudinal, antisymmetric vibration is crucial for the PAR method, because it is excited with the PAR nodes activation. The corresponding frequency should be possibly high to maximize the material damping of the induced vibration, while still allowing for timely reaction of the actuator and the controller. Obtained value of ca. $750\,Hz$ and corresponding damping value of $9.5\%$ are acceptable.

## 4. EXPERIMENTAL STAND

In order to verify the effectiveness of PAR nodes in damping of the fundamental mode of vibrations in frame structures, a simple experimental stand has been designed. Main elements of experimental set-up shown in Fig. 12 are the following:

1. frame structure,
2. semi-active PAR nodes equipped with Cedrat Technologies PPA40L actuators,
3. two channel, controllable voltage amplifier for piezo stacks actuation Cedrat LA75B-2,
4. control and data acquisition measurement card National Instruments cRio,
5. magnetic linear displacement transducer Kubler Limes LI50 (5b) with magnetic line (5a),
6. work station with LabView software for data acquisition and control.

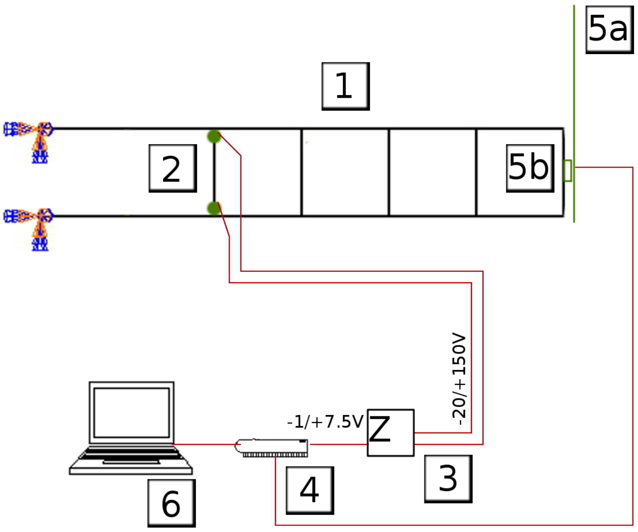


Figure 12. Schematic representation of the experimental stand.

In the initial stage eigen frequencies need to be estimated, in particular the longitudinal antisymmetric frequency. For this purpose PAR nodes in the structure excited to free vibrations will be switched from frame mode into truss mode introducing the longitudinal vibrations. The corresponding frequency and period $T_L$ of oscillation will be extracted with temporarily mounted accelerometers.

The control scheme is based on the feedback between the displacement transducer (No 5 in Fig. 12) and the voltage applied to the piezoactuators via the voltage amplifier (No 3 in Fig. 12). Upon detection of maximum displacement by the data acquisition software and hardware (No 6 and No 4 in Fig. 12) maximum voltage is applied to the piezo stacks triggering transition of PAR nodes from frame to truss mode. Then, after $T_L/2$ the frame mode is restored by means of changing the voltage in the piezo stacks to zero. The same procedure is repeated until a given damping criterion is met.

## 5. CONCLUSIONS

In this paper a semi-active, conical fit assembly has been introduced which allows for mechanical energy management, i.e. conversion of portions of mechanical energy of a vibrating frame structure between strain and kinetic energy. Parallel, low stroke and high force piezoactuators are used to modify the structural properties of the semi-active joint which can - in the frame mode - transfer maximum moment of ca. $24\,Nm$. Proposed PAR nodes can be used with the so called Prestress Accumulation Release strategy to mitigate the fundamental mode of vibrations, provided that the damped structure is significantly affected with the PAR nodes in terms of its fundamental eigen frequency. It has been shown that a simple demonstrator frame structure equipped with two semi-active nodes experience ca. $55\%$ change in the $1^{st}$ eigen frequency provided that the semi-active nodes change their state between frame and truss mode which should be sufficient to obtain a very high vibration mitigation effect.

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