# MECHATRONIC VIBRATION SETUP: EXPERIMENTS ON SYNCHRONIZATION AND CONTROL

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# Introduction

Multiresonance Mechatronic Laboratory Setup (MMLS) SV-2M of the IPME RAS was developed on the basis of many years of experience on creating vibrating stands at the Mekhanobr Engineering JSC and the IPME RAS.

It should be emphasized that Professor *Blekhman* was among the initiators of the development of the stand, he outlined the range of its possible applications in research works on vibration technologies, the mechanical resonance phenomena and oscillations synchronization. *I.I. Blekhman* had paid great attention to the works performed on the setup, actively participated in the discussion, helped interpretation of experimental results and had suggested the directions for further research.

## Setup Description

The MMLS includes:

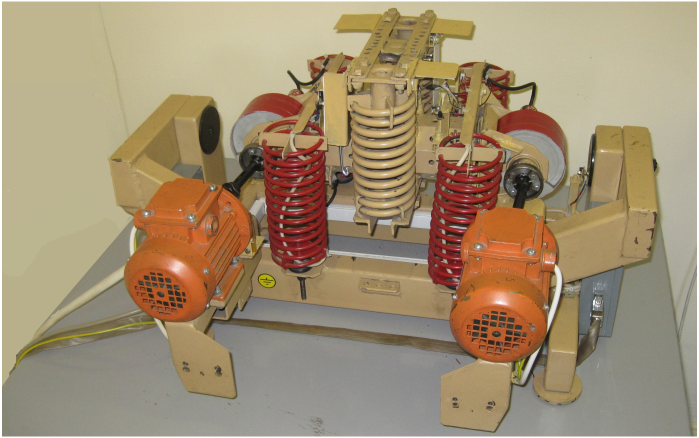
- *vibrational stand*;
- *electrical motors*;
- *sensors*;
- *personal computer* (PC).

All the devices constitute an integrated system, where the electrical and mechanical processes are closely linked each other.

# Setup Description. General view

# Setup Description. Mechanical part

Mechanical part – electrically driven vibrational device:



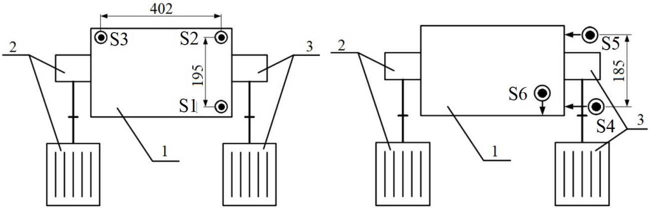
1 – induction motors, 2 – support frame, 3 – springs, 4 – additional frame, 5– unbalanced rotors

## Setup Description. Mechanical part

- Key part – a pair of the unbalanced (centrifugal) actuators.
- Each actuator includes:
    - three-phase induction motor (1) with computer-controlled rotation velocity;
    - the unbalanced rotor (5), which rotates on the motor shaft. Unbalance of the rotor is provided by the eccentrically located weight.
- The drive shafts and the anti-vibration screw springs reduce the vibration transmission to the frame (2) and the basis.
- The additional platform (4) is mounted on the springs (3) for installing the additional weight.

# Setup Description. Sensors

- 12 *optical sensors* measuring the linear displacements of both platforms are installed. The sensors' data allow to obtain information about the 6DoF linear and angular coordinates of platform;
- 2 *three-axis* accelerometers are installed on each platform;
- motor rotors are equipped with *encoders* measuring the increments of rotor angles in the amount of 4000 bits per revolution.



# Control of Phase Shift and Vibrational Fields

If the different points of the supporting platform oscillate along different trajectories, the field of vibrations is nonuniform:

**V. L. Chelomey, Ed., Vibration in Engineering. Handbook. M., 1978–1981, vol. 4, (in Russian)**

Ensuring an appropriate vibrational field of the platform is important for bulk materials transportation.
The self-synchronization phenomenon without kinematic connections between the actuators may be used:

**Blekhman, Fradkov, Nijmeijer, Pogromsky, "On self-synchronization and controlled synchronization," Systems & Control Letters, 1997.**

Additional possibilities: feedback control, ensuring prespecified steady phase difference between the rotors.

# Modeling the Drive System

SV-2M properties were roughly studied in the open-loop by applying constant control signals of various levels to the drive systems. Partition of the rotation frequency:

1. *low frequencies*: $0 \leqslant \omega < 30$ rad/s; the significant impact of the gravitational "pendular" torque to motors;
2. *medium frequencies*: $30 \leqslant \omega < 70$ rad/s;
3. *high frequencies*: $70 \leqslant \omega < 100$ rad/s;
4. *superior frequencies*: $\omega \geqslant 100$ rad/s; very strong interaction between the rotating debalances and movement of the platforms;
   close to $\omega \approx 125$ rad/s – *Sommerfeld* effect.

Low and superior frequencies are not considered in this study.

## Modeling the Drive System (cont.)

In medium and high frequency ranges, the *averaging property* is valid – fast oscillating components are averaged and only the "slow" motions may be taken into account.
Drive system (induction motor + frequency converter + local controller) dynamics approximately described by:

$$W_d(s) = \left\{\frac{\omega}{u}\right\} = \frac{k_d}{(Ts+1)(\tau s+1)}, \qquad (1)$$

$k_d$ – static gain; $T$ and $\tau$ – time constants.
Standard non-recursive LSE method was used to find $k_d$, $T$, $\tau$.
Obtained that variations of model (1) parameters for different regions of base frequency are small. The "averaged" values $k_d = 0.041$ rad/s, $T = 1.75$ s, $\tau = 0.246$ s are taken.

## Control Algorithms

Control algorithms: ensuring prescribed phase shift $\psi = \varphi_l - \varphi_r$ between $\varphi_l(t)$, $\varphi_r(t)$ & speed $\omega_l = \omega_r = \omega^*$.

1. Feedback control of rotor angular velocities

Stabilizing rotor velocities $\omega_l$, $\omega_r$ around given $\omega_l^*$, $\omega_r^*$ by

$$\text{PI}_\omega\text{-controller:} \quad \begin{cases} e_{l,r} = \omega_{l,r}^*(t) - \omega_{l,r}(t) \\ \dot{\sigma}_{\omega_{l,r}} = e_{l,r}(t), \quad \sigma_{\omega_{l,r}}(0) = 0, \\ u_{\omega_{l,r}} = k_{P_\omega} e_{l,r}(t) + k_{I_\omega} \sigma_{\omega_{l,r}}(t), \end{cases} \tag{2}$$

$\omega_{l,r}^*(t)$ – reference angular velocities; $\omega_{l,r}(t)$ – actual velocities; $u_{\omega_{l,r}}$ – control signals. $k_{P_\omega} = 1260$ s/rad, $k_{I_\omega} = 730$ 1/rad $\Rightarrow$ gain margin $G_m = \infty$, phase margin $P_m = 58$ deg, overshoot $= 11$ %, $5\%$-setting time $= 1.5$ s, $H_\infty = 1.05$.

# Control Algorithms (cont.)

## 2. Feedback control of the phase shift and angular velocities

Cross-coupling between the drives by introducing $u_\psi$:

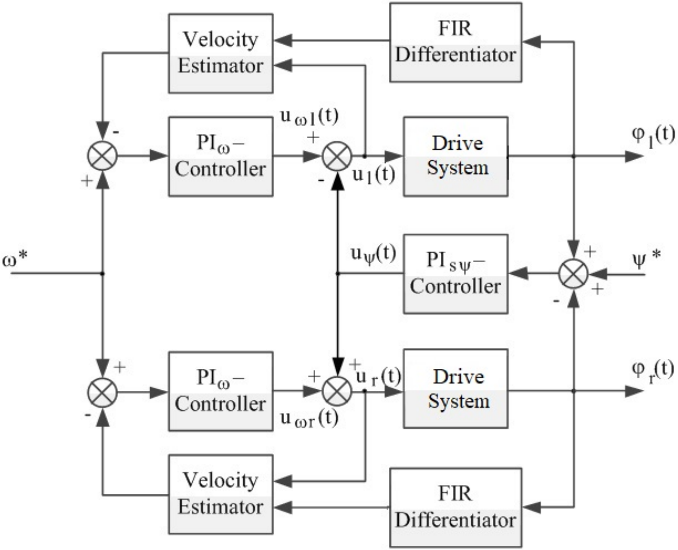
$$u_l(t) = u_{\omega_l}(t) - u_\psi(t), \quad u_r(t) = u_{\omega_r}(t) + u_\psi(t), \qquad (3)$$

$u_{\omega_l}$, $u_{\omega_r}$ – outputs of PI$_\omega$-controllers (2), $u_\psi$ is computed based on error between phase shift $\psi(t) = \varphi_l - \varphi_r$ and its desired value $\psi^*$, i.e. $\Delta\psi(t) = \psi^* - \psi(t)$:

$$\text{PI}_{s\psi}\text{-controller:} \quad \begin{cases} \psi(t) = \varphi_l(t) - \varphi_r(t), \\ \Delta\psi(t) = \psi^* - \psi(t), \\ \dot{\sigma}_\psi(t) = \sin\left(\Delta\psi(t)\right), \\ u_\psi(t) = k_{P_\psi} \sin\left(\Delta\psi(t)\right) + k_{I_\psi}\sigma_\psi(t), \end{cases} \qquad (4)$$

In this *sine modification*, $\sin\left(\Delta\psi(t)\right)$ is used instead of $\Delta\psi(t)$.

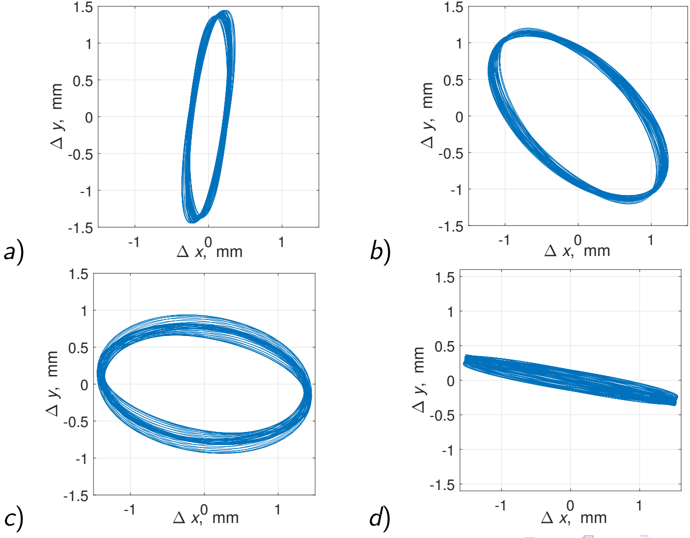
# Controller block-diagram



## Experimental Results for Phase Shift Control

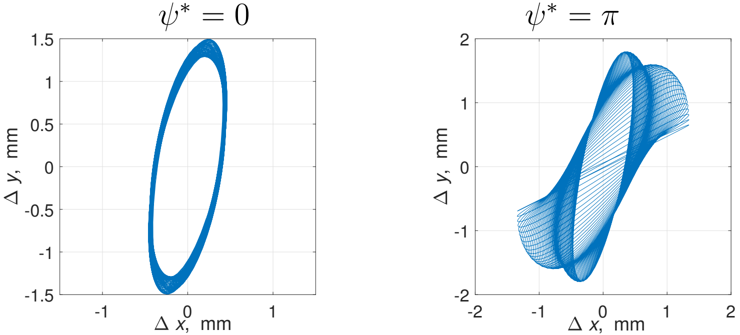
1. Low frequency $\omega^* = 30$ rad/s
   Angular velocity and phase shift errors are relatively high due to a significant impact of the debalance torque to the drives.
2. Medium frequency $\omega^* = 60$ rad/s
   Both frequency and phase shift errors are not significant.
3. High frequency $\omega^* = 80$ rad/s
   For $\psi^* = \pi$ rad, the desired phase shift $\psi = \pi$ can't be ensured since control action is unable to overcome the tendency of self-synchronization in phase of the unbalanced rotors, revolving with a high velocity.

## Platform oscillations $\Delta y = v(\Delta x)$. $\omega^* = 60$ rad/s.
## *a*) $\psi^* = 0$, *b*) $\psi^* = \pi/2$ rad, *c*) $\psi^* = 3\pi/4$ rad, *d*) $\psi^* = \pi$ rad



# Experimental Results (cont.)

Platform oscillations $\Delta y = v(\Delta x)$. $\omega^* = 80$ rad/s

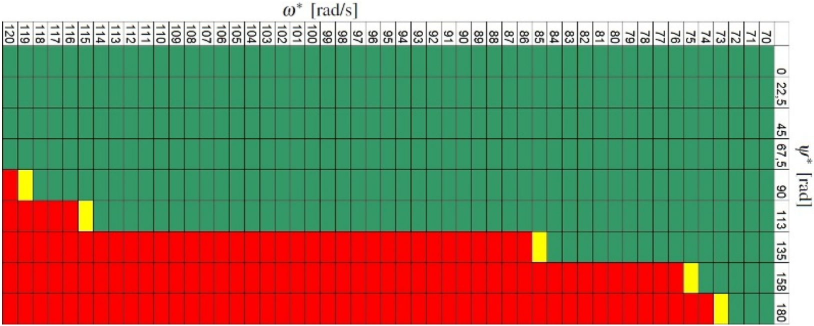


## Summarizing Diagram. Attainability Domain

green: $\psi^*$ may be ensured;

red: stable rotation with a given $\psi^*$ is not possible.

yellow: intermediate domain.



# Conclusion

The problem of controlled synchronization for unbalanced rotors phase shift is considered. The control laws for frequency stabilization along with the prescribed phase shift between the rotors angular positions are proposed and experimentally studied on the mechatronic vibration stand SV-2M. It is obtained that for the low and medium frequencies the selfsynchronization of unbalanced rotors does not prevent ensuring the desired phase shift between the rotors. For a high frequency band, the Huygens self-synchronization of rotors manifests itself, narrowing the range of the achievable phase shift. Nevertheless for all the frequencies less than the frequency of the Sommerfeld effect, the desired phase shift in the range of $\pi/2$ rad can be ensured.

## Bibliography

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