A R C H I V E O F M E C H A N I C A L E N G I N E E R I N G

DOI: 10.24425/ame.2026.12619 Early Access; pp. 1–28

Tomasz KĄDZIOŁKA [1]

Kinematic and experimental investigation of the mechanical characteristics of a tracker-action pipe organ

Received 26 July 2026, **Revised** 17 September 2026, **Accepted** 17 October 2026, **Published online** 19 November 2025

Keywords: mechanical tracker-action organ; operational characteristics; kinematic analysis; key actuation force; organ maintenance; pipe organ

This paper investigates changes in the operational characteristics of a mechanical tracker-action pipe organ following a comprehensive renovation in 2024. The study focuses on the key actuation force in relation to the mechanical condition of the tracker action and separately examines the effects of wind pressure in the wind chest and mechanical loading introduced by manual couplers. The key and stop actions were analyzed using kinematic diagrams, and their mobility was determined according to classical kinematic theory. Experimental measurements were performed using a digital force gauge. Pre- and post-renovation measurements under identical unpressurized conditions, with the blower switched off, showed a decrease in maximum key actuation force from 4.5 N to 2.3 N (2.2 N reduction), indicating substantially reduced mechanical resistance of the tracker action. Separate post-renovation measurements showed that wind pressure at the reported nominal 75 mm H_2O increased the key actuation force by up to 1.9 N, while engagement of manual couplers increased it to 9.4 N. These results demonstrate that mechanical condition, wind pressure, and coupler loading contribute to the key actuation force. Such measurements may provide a quantitative indicator for assessing tracker-action condition and supporting maintenance and renovation of historical pipe organs, although they characterize movement initiation rather than complete force–displacement behavior.

✉ Tomasz KĄDZIOŁKA, e-mail: tkadziolka@ans-ns.edu.pl

[1]Faculty of Engineering Sciences, University of Applied Sciences in Nowy Sącz, 1a Zamenhofa street, 33-300 Nowy Sącz, Poland.

© 2026. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution (CC-BY 4.0, https://creativecommons.org/licenses/by/4.0/), which permits use, distribution, and reproduction in any medium, provided that the author and source are cited.

1. Introduction

Mechanical tracker-action pipe organs constitute complex multibody systems in which motion generated by the organist is transmitted directly from the manual keys to the pallet valves through trackers, levers, roller shafts, squares, and other transmission components. Unlike pneumatic, electromagnetic, or mechatronic actions, tracker action provides direct mechanical coupling between the performer and the pallet valves, enabling precise control of valve opening and immediate tactile feedback [1–5].

The operational characteristics of a tracker-action organ depend strongly on the design, adjustment, and technical condition of its mechanical transmission system. Friction in bearings and guides, wear, clearances in kinematic joints, action alignment, pallet spring forces, and aerodynamic forces acting on the pallet valves contribute to the force required to operate the keys. Wear, deterioration, or maladjustment may therefore increase mechanical resistance and the loading of action components, requiring periodic adjustment and maintenance [6–8].

Environmental conditions and the wind supply system also influence historical pipe organs. Temperature and relative humidity affect pipe tuning and wooden mechanical components, potentially causing dimensional changes, increased friction, or sticking of stop sliders [9–12]. The wind supply system determines the pressure delivered to the wind chest and its stability. In a mechanical tracker action, wind pressure introduces an aerodynamic load on the pallet valves that must be overcome through the key-action mechanism. Key actuation force may therefore differ between pressurized and unpressurized conditions. Quantitative determination of wind-system parameters is important for the documentation and reconstruction of historical organs, with recent studies applying predictive, machine-learning, and pattern-recognition methods to these tasks [13–15].

Previous studies have quantitatively investigated mechanical tracker actions. Asutay [16] examined mechanical key actions using objective measurements and subjective characterization, while Woolley [8, 17] investigated their physical characteristics and relationship to musical performance [8, 17, 18]. However, direct experimental comparisons of key actuation forces in the same historical instrument before and after comprehensive renovation remain limited. Moreover, the effects of mechanical condition, wind pressure, and manual couplers on key actuation force have rarely been experimentally separated.

This study quantitatively evaluates changes in the operational characteristics of the mechanical tracker-action pipe organ in St. Lawrence's Church in Nowy Sącz–Biegonice following its comprehensive renovation in 2024. Kinematic analysis of the key and stop actions was combined with experimental measurements of key actuation force. The principal pre- and post-renovation comparison was performed under identical unpressurized conditions, with the blower switched off, allowing changes in mechanical resistance to be evaluated independently of aero-

dynamic loading. Thus, differences in nominal operating pressure before and after renovation did not affect this comparison.

The influence of wind pressure was investigated separately after renovation by comparing key actuation forces under unpressurized conditions with those measured at the post-renovation nominal pressure of 75 mm H_2O. Additional measurements with the manual couplers engaged were used to evaluate the mechanical loading introduced by the coupled actions.

Accordingly, the study addresses three research questions: (1) To what extent did the key actuation force under unpressurized conditions change following renovation? (2) What additional key actuation force is associated with wind pressure and manual couplers after renovation? (3) Can the key actuation force provide a quantitative indicator of changes in the mechanical condition of a historical tracker action?

1.1. The history of the instrument

The pipe organ investigated in this study is installed in St. Lawrence's Church in Nowy Sącz-Biegonice [20]. According to Pasternak [19], it was built in 1910 by Tomasz Fall from Szczyrzyc and substantially rebuilt in 1929 by Bartłomiej Ziemiański, a former pupil of Fall. During this reconstruction, the instrument was moved further into the organ gallery and equipped with a detached console facing the altar; the organ case may also have been modified [19]. A general view of the organ after the 2024 renovation is shown in Fig. 1. Before 1949, an electric blower was installed, and no major reconstruction between 1949 and 2000 is documented. The next documented renovation was carried out in 2007 by Mieczysław Ziemiański [19].



Fig. 1. General view of the investigated mechanical tracker-action pipe organ in St. Lawrence's Church in Nowy Sącz–Biegonice

The 2007 renovation included repairs to the wind chest and tracker action, replacement of the pedal stops Subbas 16′ and Flauto 8′, installation of a new blower, and replacement of the original reservoir-and-feeder bellows with a smaller reservoir bellows. Despite these works, some mechanical deficiencies remained. Prior to the 2024 renovation, the reported wind pressure was approximately 65 mm H_2O.

A comprehensive renovation was carried out between February and July 2024. It included replacement of worn bearing components in the key and stop actions, repair of damaged tuning sections of the metal pipes (Fig. 2), sealing of the wind chest, modernization of the blower system and electrical controls, installation of an air filter, and complete regulation, voicing, and tuning. According to the organ builders, the wind pressure was set to 75 mm H_2O; this value was not independently verified by the author. The pitch standard was changed from approximately $a^1 \approx$ 420 Hz to $a^1 = 440$ Hz.

The changes in wind pressure and pitch standard characterize the pre- and post-renovation states, but did not affect the principal comparison of key actuation



(a) (b)

Fig. 2. Pipe condition before (a) and after (b) the 2024 renovation



(a) (b)

Fig. 3. Components of the organ control system: (a) bellows fill-level control mechanism; (b) control levers for the manual couplers (labelled “Octave Koppel”) and the expression shutters

force, which was performed under identical unpressurized conditions with the blower switched off. The influence of wind pressure was investigated separately after renovation, as described in Section 3.

2. Organ design and mechanical structure

The investigated instrument is a single-manual mechanical tracker-action pipe organ with a pedal division and ten speaking stops. It employs a traditional slider wind chest with mechanical key and stop actions [21–23]. A schematic representation of the principal components and their functional relationships is shown in Fig. 4.

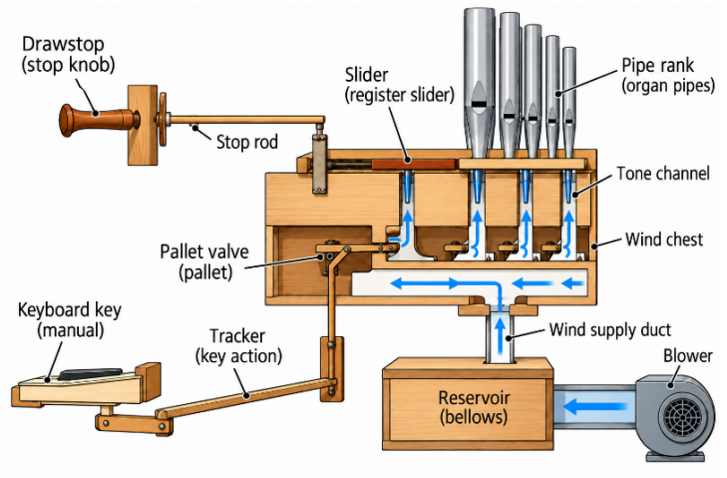


Fig. 4. Schematic representation of the mechanical tracker action and wind system of the investigated pipe organ

The pipes are arranged in ranks corresponding to individual stops, while each tone channel supplies the pipes associated with a particular key. Operating a drawstop displaces the corresponding slider, aligning its holes with the selected pipe rank. When a key or pedal is depressed, motion is transmitted mechanically through the tracker action to the corresponding pallet valve, allowing pressurized air from the pallet box to enter the tone channel and sound the selected pipes [24].

The key action transmits motion from the manual keys to the pallet valves through wooden trackers, levers, roller shafts, squares and pallet-actuating rods, without pneumatic or electromechanical assistance (Fig. 9). The stop action forms a separate mechanical transmission in which motion from the drawstops is transmitted to the sliders through wooden levers and metal squares (Fig. 8). Mechanical resistance in these systems may be influenced by bearing friction, alignment, clearances and the condition of their components [25].

The organ employs a crosswise slider wind chest operating according to the pallet-and-slider principle, with pipes arranged on separate C and C♯ sides [26]. Pallet dimensions vary across the compass, with larger pallets in the bass and progressively smaller pallets for higher notes. Consequently, the key actuation force may depend on the transmission geometry, pallet dimensions, spring forces, and mechanical friction, and – under pressurized conditions – the aerodynamic force acting on the pallet valve [27].



(a) (b)

Fig. 5. View of the stops in the organ console

To distinguish these effects, changes associated with renovation were evaluated by comparing pre- and post-renovation key actuation forces under identical unpressurized conditions. The influence of wind pressure was investigated separately after renovation by comparing measurements with the wind chest unpressurized and pressurized, as described in Section 3.

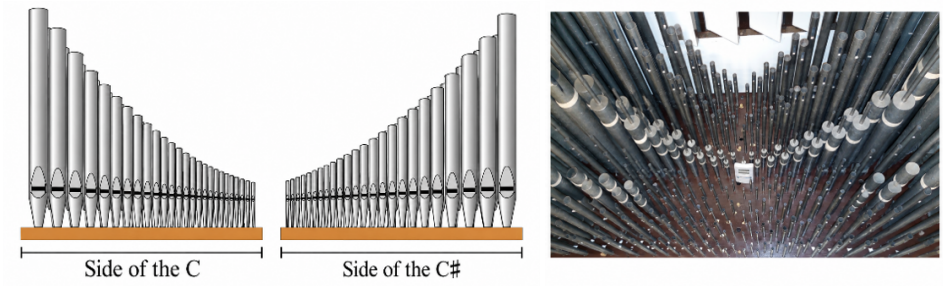


Fig. 6. Schematic arrangement of the pipework between the C and C♯ sides of the slider wind chest. Author's own elaboration

For structural analysis, the stop and key actions were represented by planar kinematic diagrams (Figs. 8 and 9). The stop action model consists of nine moving links connected by twelve lower and two higher kinematic pairs, whereas the key action model comprises nine moving links connected by thirteen lower

kinematic pairs. Their mobility is determined in Section 3.3 using the Chebyshev–Grübler–Kutzbach criterion for planar mechanisms. This analysis characterizes the kinematic structure and mobility of the mechanisms and is not used to determine the key actuation force.

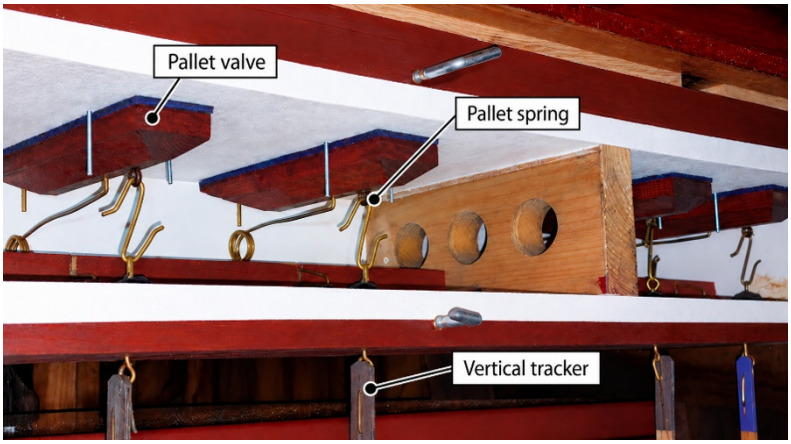


Fig. 7. Components of the pallet valve actuation mechanism inside the wind chest

3. The object of investigations and methodology

The object of the investigation was the mechanical tracker-action pipe organ installed in St. Lawrence's Church in Nowy Sącz–Biegonice. The study focused on changes in the key actuation force associated with the comprehensive renovation carried out in 2024 and was designed to distinguish between the mechanical resistance of the tracker action and the additional contributions of wind pressure and manual couplers.

The mechanical structures of the key and stop actions were represented by kinematic diagrams and analyzed using classical kinematic theory [28–31]. Their mobility was determined using the Chebyshev–Grübler–Kutzbach criterion for planar mechanisms. This analysis characterized the kinematic structure and mobility of the mechanisms and was not used to calculate the key actuation force.

The experimental investigation comprised three separate comparisons. First, the effect of renovation on the mechanical resistance of the key action was evaluated by comparing key actuation forces measured before and after renovation under identical unpressurized conditions, with the blower switched off. Under these conditions, the pallet valves were not subjected to aerodynamic loading from wind pressure; therefore, the measured force predominantly reflected mechanical resistance, including friction and resistance associated with moving components and valve springs.

Second, the influence of wind pressure was investigated after renovation by comparing key actuation forces measured with the wind chest unpressurized and pressurized to the reported nominal value of 75 mm H_2O. This comparison evaluated the additional contribution associated with wind pressure acting on the pallet valves and was independent of the principal pre- and post-renovation comparison.

According to the organ builders responsible for the respective interventions, the nominal wind pressure was approximately 65 mm H_2O after the 2007 renovation and 75 mm H_2O after the 2024 renovation. These values and their determination methods were not independently verified and are therefore reported only as technical information characterizing the operating states of the instrument.

Third, the influence of the Octave Koppel manual couplers was investigated after renovation by measuring key actuation forces with the couplers engaged. These measurements were used to evaluate the additional mechanical loading introduced by the coupled mechanisms and were analyzed separately from the renovation and wind-pressure comparisons.

The methodology thus distinguishes between changes in mechanical resistance associated with renovation, aerodynamic loading due to wind pressure, and mechanical loading introduced by the manual couplers. Key actuation force is interpreted as a quantitative characteristic of key-action operation and changes in its mechanical condition rather than as a complete measure of keyboard toucher or playing ergonomics [8, 16, 17].

3.1. Experimental procedure

Experimental measurements were performed during two campaigns: 14–18 August 2023, before the comprehensive renovation, and 15–19 July 2024, after its completion. Air temperature and relative humidity inside the church were monitored during both campaigns to document the environmental conditions (Figs. 11 and 12) [9–11].

Key actuation force was measured using a SOONDA Digital Force Gauge, Model S-300, with an accuracy better than ±0.1 N. Prior to the measurements, the force gauge was verified using calibrated laboratory weights. The force was applied at the same position on each investigated key and increased gradually until the defined actuation point was reached.

Key actuation force was defined as the force recorded at the onset of key-action movement leading to pallet-valve actuation. This definition was applied consistently throughout the study. The measured value therefore characterizes the force required to initiate key-action operation rather than its complete force–displacement behaviour or the tactile characteristics of the key throughout its full travel [8, 16, 17].

The principal pre- and post-renovation comparison was performed under identical unpressurized conditions, with the blower switched off and the wind chest unpressurized in both campaigns. Representative keys distributed across the man-

ual compass were investigated to evaluate changes in the mechanical resistance of the key action across different regions of the keyboard.

A separate post-renovation series investigated the influence of wind pressure. For each key, measurements obtained with the wind chest unpressurized were compared with those obtained with the blower operating and the wind chest pressurized to the reported nominal value of 75 mm H_2O. The difference between these values was used to evaluate the increase in key actuation force associated with wind pressure acting on the pallet valve.

Additional post-renovation measurements were performed with the Octave Koppel manual couplers engaged to evaluate the additional mechanical loading introduced by the coupled mechanisms. These measurements were analyzed separately from the principal pre- and post-renovation comparison and the wind-pressure experiment.

For each investigated key and measurement condition, ten repeated measurements ($n = 10$) were performed. The results are reported as arithmetic means, with measurement variability characterized by the standard deviation (SD). The position of the force gauge on the key and the measurement procedure were maintained consistently throughout the measurements.

The pitch standard changed from approximately $a^1 \approx 420$ Hz before renovation to $a^1 = 440$ Hz after renovation. This difference is reported as part of the technical characterization of the instrument and did not constitute a variable in the principal unpressurized key-force comparison.

3.2. Statistical analysis

For each investigated key and measurement condition, ten repeated force measurements ($n = 10$) were obtained. The arithmetic mean and standard deviation (SD) were calculated, and the results are reported as mean ±SD. The SD was used to characterize measurement variability and repeatability.

Differences in mean key actuation force were evaluated in relation to both measurement variability and the stated accuracy of the digital force gauge (better than ±0.1 N). Differences approaching the accuracy of the measurement method were interpreted with caution and were not considered evidence of a meaningful change in key actuation force.

The three experimental comparisons – renovation, wind pressure, and manual-coupler loading – were analyzed separately according to the conditions described in Section 3.1.

The statistical analysis was descriptive and intended to characterize the magnitude and repeatability of the measured key actuation forces. No conclusions regarding statistical significance were drawn solely from the overlap or non-overlap of the SD error bars.

3.3. Kinematic analysis of the stop and pallet valve actuation mechanisms

The kinematic analysis was performed to characterize the structural configuration of the investigated stop and pallet valve actuation mechanisms and to determine their mobility. The analysis provides a structural description of the mechanical transmission systems and identifies the number of independent motions required for their operation. It should be emphasized that the kinematic analysis is used here solely to characterize the structure and mobility of the mechanisms and is not used to determine the magnitude of the key actuation force.

The kinematic diagrams of the stop and pallet valve actuation mechanisms were analyzed using classical structural methods for planar mechanisms [28, 30, 31]. From the structural point of view, the mechanisms were classified according to Assur's structural classification. Independent of this classification, their mobility was determined using the Chebyshev–Grübler–Kutzbach criterion for planar mechanisms [28, 30, 31]:

$$W' = 3n_r - 2p_5 - p_4\,, \tag{1}$$

where:

W' – the mobility of the mechanism,

n_r – the number of moving links in the mechanism, excluding the fixed link,

p_5 – the number of lower kinematic pairs,

p_4 – the number of higher kinematic pairs [28, 30, 31].

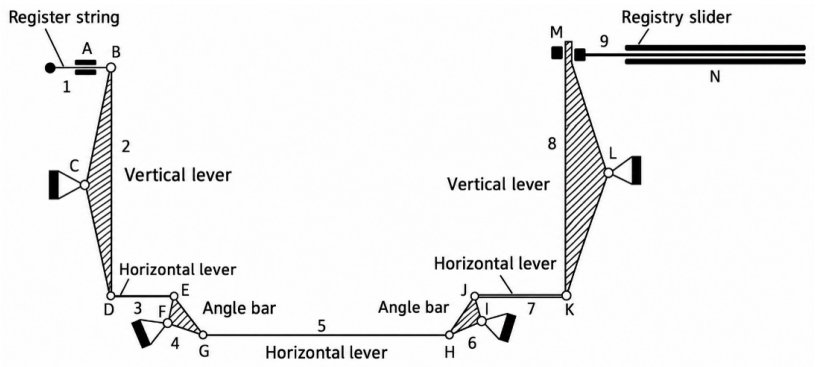


Fig. 8. Stop action mechanism

In the mechanism under analysis (Fig. 8):

$n_r = 9$,

$p_5 = 12$,

$p_4 = 2$,

hence mobility $W' = 1$.

In the same manner, the mobility of the mechanism transmitting the motion of key 1 to pallet valve 9, shown in Fig. 9, was determined. Based on Eq. (1) and the kinematic diagram, the following parameters were identified:

$n_r = 9$,
$p_5 = 13$,
$p_4 = 0$.

Hence, the mobility of the mechanism is $W' = 1$.

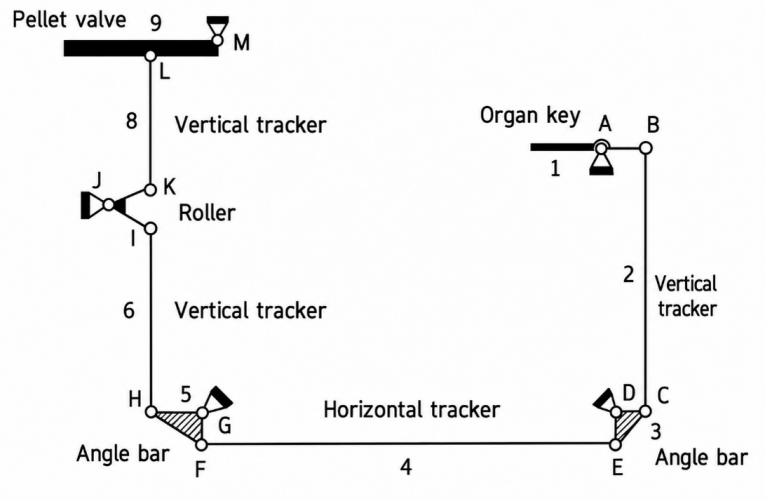


Fig. 9. Pallet valve actuation mechanism

The calculated mobility confirms that the investigated stop and pallet valve actuation mechanisms each possess a single degree of freedom. Consequently, the motion of a single input element – the manual key in the key action (Fig. 9) or the stop knob in the stop action (Fig. 8) – determines the motion of the corresponding pallet valve or stop slider through the intermediate links of the mechanical transmission system.

The mobility analysis, therefore, provides a structural and kinematic characterization of the investigated mechanisms. It confirms their single-degree-of-freedom configuration but does not determine the forces acting within the mechanisms or the magnitude of the key actuation force. The key actuation forces were determined independently by experimental measurements described in the following sections.

3.4. Operational problems of the investigated pipe organ

As described in Section 1.1, the investigated pipe organ was built in 1910 and underwent several modifications and repairs during its operational history. Following the 2007 renovation, the instrument remained in regular use until February 2024, when a comprehensive renovation was initiated because of its deteriorated

technical condition. Prior to renovation, woodworm infestation was identified in wooden components, while the key and stop actions exhibited considerable wear. Metal pipes showed damage to their tuning sections (Figs. 2a and 10d), wear and maladjustment affected bearings, guides, and regulating elements of the mechanical transmission system. Visible wear was also present on the manual keys (Fig. 10c). The Octave Koppel manual couplers required readjustment, with one control lever detached (Fig. 10b), while the tracker wires required replacement of worn shims and readjustment using the regulating screws (Fig. 10a) [6, 7].



(a) (b)

(c) (d)

Fig. 10. Examples of instrument damage and mechanical deficiencies identified before the 2024 renovation: (a) tracker-action components; (b) super-octave coupler mechanism; (c) worn manual keys; (d) damaged tuning sections of metal pipes

Since friction, wear, and maladjustment of the transmission components contribute to the mechanical resistance of a tracker action [6–8, 17], the key actuation force was selected as a quantitative parameter for evaluating changes in the mechanical condition of the key action associated with the 2024 renovation.

Key actuation forces measured before renovation in August 2023 and after renovation in July 2024 were compared under identical unpressurized conditions, with the blower switched off. This allowed changes in mechanical resistance to be evaluated independently of differences in nominal wind pressure. The detailed measurement procedure and statistical treatment are described in Sections 3.1 and 3.2.

The manual compass extends from C to f^3. Representative keys C, $C^\sharp$, E, $F^\sharp$, A, and B were selected within the C–c^3 range, while all keys from c^3 to f^3 were investigated. The pre- and post-renovation results are presented and discussed in the following section.

4. Results of investigations of the organ in Biegonice

The pre-renovation measurements were carried out between 14 and 18 August 2023. During this period, the air temperature inside the church ranged from 21.2 to 24.8°C, while the relative humidity varied between 50% and 56% (Fig. 11). The post-renovation measurements were performed between 15 and 19 July 2024, with air temperatures ranging from 23.2 to 25.3°C and relative humidity between 53% and 57% (Fig. 12). The environmental conditions recorded during the two measurement campaigns were therefore similar, although not identical. Temperature and relative humidity were monitored because variations in these parameters may affect wooden components and the mechanical operation of historical pipe organs [9–11].

For each investigated key and measurement condition, ten repeated force measurements ($n = 10$) were performed. The arithmetic mean of the repeated measurements was calculated for each investigated key and used for the comparison of

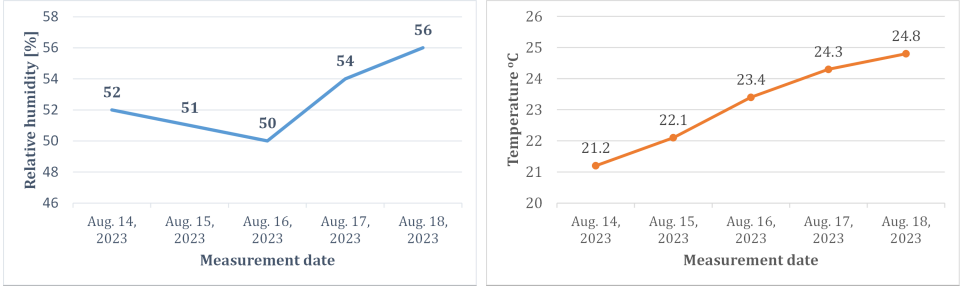


Fig. 11. Air temperature and relative humidity recorded during the pre-renovation measurement campaign

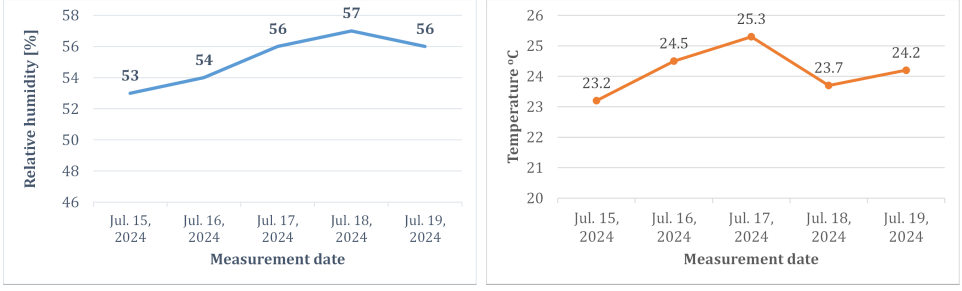


Fig. 12. Air temperature and relative humidity recorded during the post-renovation measurement campaign

the pre- and post-renovation results. The variability of the repeated measurements was characterized using the standard deviation (SD) calculated from the individual force readings.

The principal comparison of the pre- and post-renovation results was performed under identical unpressurized conditions, with the blower switched off during both measurement campaigns. Consequently, the pallet valves were not subjected to aerodynamic loading resulting from wind pressure. This experimental arrangement allowed changes in key actuation force associated predominantly with changes in the mechanical resistance of the tracker action to be evaluated independently of the difference between the nominal pre- and post-renovation wind pressures.

Figs. 13–17 compare the mean key actuation forces measured before and after the comprehensive renovation carried out in 2024. A reduction in the mean key actuation force was observed for all investigated keys. The largest reduction was 2.2 N for the e key (Fig. 14), for which the mean key actuation force decreased from 4.5 N before renovation to 2.3 N after renovation. The results, therefore, show a clear reduction in the key actuation force following renovation under the investigated unpressurized conditions.

The reduction in key actuation force coincided with extensive mechanical work carried out during the 2024 renovation. This work included replacement of worn bearing components in the roller shafts, squares and manual keys (Figs. 18a–18d), adjustment of the mechanical transmission system, and installation of appropriately selected pallet-valve springs (Fig. 7). Felt shims were also replaced, and regulating nuts were installed on the tracker wires (Fig. 18a), allowing the geometry and adjustment of the pallet-valve actuation mechanism to be restored. These interventions addressed sources of mechanical resistance, wear, play, and maladjustment identified before renovation.

The observed reduction in key actuation force is consistent with a decrease in the mechanical resistance of the tracker action following renovation. However, the present measurements do not allow the contributions of individual mechanical components or phenomena, such as bearing friction, spring force, alignment, or mechanical play, to be quantified separately. Accordingly, the measured reduction should be interpreted as the combined effect of the mechanical interventions performed during renovation rather than being attributed quantitatively to any single component.

The results demonstrate that repeated measurements of key actuation force can provide a quantitative parameter for comparing the mechanical condition of the same tracker action before and after renovation when the measurements are performed under controlled and comparable conditions. In the present study, the use of identical unpressurized conditions for the principal pre- and post-renovation comparison made it possible to separate this comparison from the aerodynamic contribution associated with wind pressure. The influence of wind pressure and the additional mechanical loading introduced by the manual couplers are analyzed separately in the following sections.

Fig. 13 presents the mean key actuation forces for six selected keys in the first manual octave before and after the 2024 renovation. A reduction in the mean key actuation force was observed for all investigated keys. The decrease ranged from 1.1 N for the B key (from 3.8 N to 2.7 N) to 1.9 N for the E key (from 3.9 N to 2.0 N). The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition (n = 10).

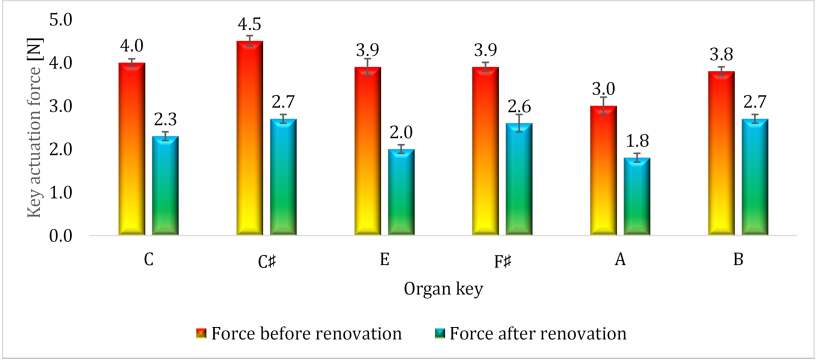


Fig. 13. Key actuation force for selected keys in the C–c octave before and after renovation (mean ± SD, n = 10)

Fig. 14 presents the mean key actuation forces measured for the selected keys in the second manual octave before and after the 2024 renovation. A reduction in the mean key actuation force was observed for all investigated keys. The decrease ranged from 1.0 N for the A key to 2.2 N for the e key.

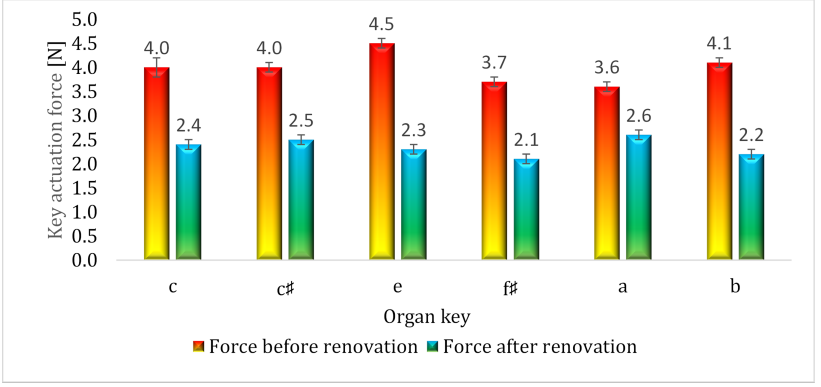


Fig. 14. Key actuation force for selected keys in the c–c^1 octave before and after renovation (mean ± SD, n = 10)

Fig. 15 presents the mean key actuation forces measured for the selected keys in the third manual octave before and after the 2024 renovation. A reduction in

the mean key actuation force was observed for all investigated keys. The decrease ranged from 0.7 N for the e^1 key to 1.6 N for the b^1 key.

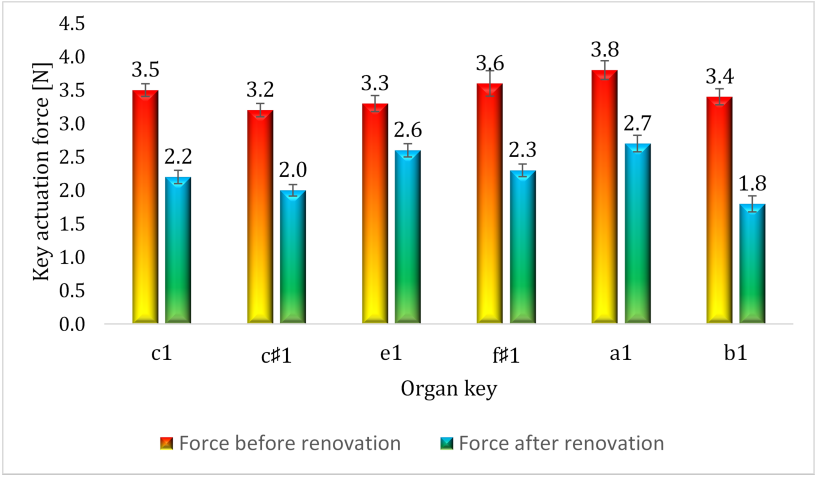


Fig. 15. Key actuation force for selected keys in the c^1–c^2 octave before and after renovation (mean ± SD, n = 10)

Fig. 16 presents the mean key actuation forces measured for the selected keys in the fourth manual octave before and after the 2024 renovation. A reduction in the mean key actuation force was observed for all investigated keys. The decrease ranged from 0.4 N for the c^2 key to 0.8 N for the $f♯^2$ and b^2 keys.

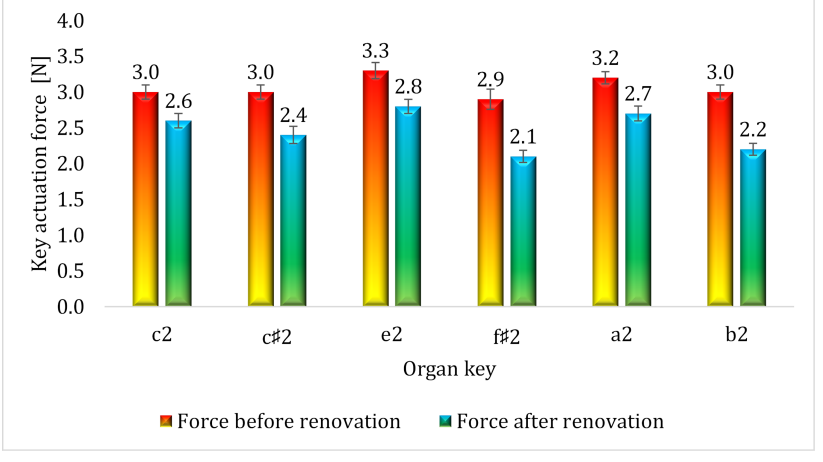


Fig. 16. Key actuation force for selected keys in the c^2–c^3 octave before and after renovation (mean ± SD, n = 10)

Fig. 17 presents the mean key actuation forces measured for the highest manual key range (c^3–f^3) before and after the 2024 renovation. A reduction in the mean key

actuation force was observed for all investigated keys, ranging from 1.0 N to 1.9 N. Despite this reduction, the post-renovation key actuation forces in the c^3–f^3 range remained slightly higher than those measured in the preceding manual octave. This variation may be associated with local differences in geometry, adjustment, and mechanical resistance of the key action along the manual compass.

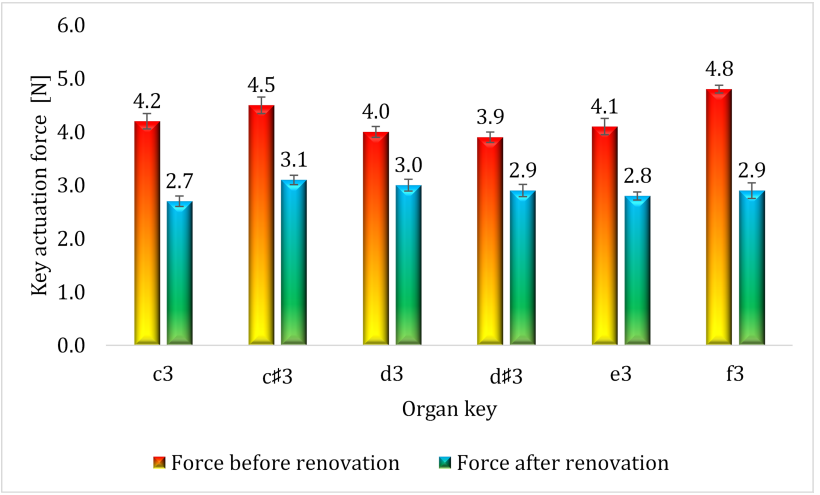
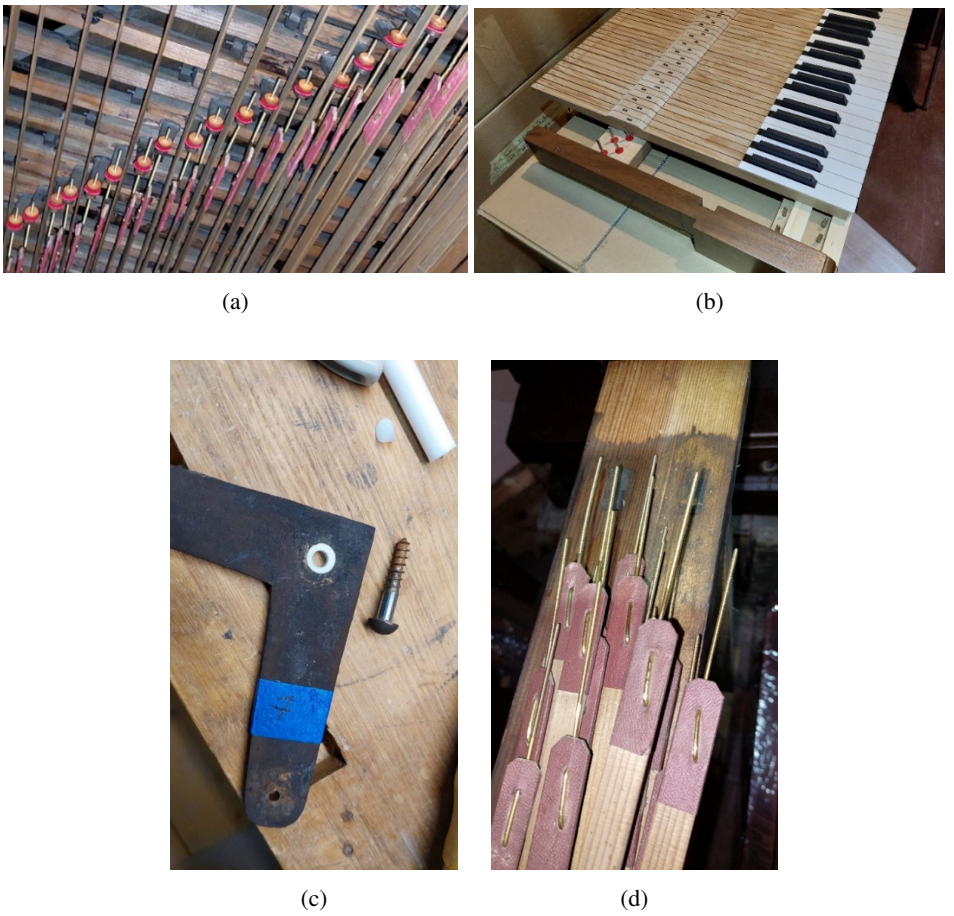


Fig. 17. Key actuation force for selected keys in the c^3–f^3 range before and after renovation (mean ± SD, n = 10)

The results demonstrate that the key actuation force varies across the manual compass and was reduced following the 2024 renovation. In a mechanical tracker action, the force applied to a key is transmitted through the mechanical linkage to the corresponding pallet valve. Variations in geometry, adjustment, and mechanical resistance of the linkage may therefore influence the measured key actuation force. The measurements obtained in this study provide a quantitative parameter for comparing the mechanical condition of the key action before and after renovation.

To determine the influence of wind pressure on the key actuation force, a separate series of measurements was performed after the 2024 renovation. Measurements obtained with the blower switched off, and the wind chest unpressurized, were compared with those obtained with the blower operating and the wind chest pressurized to the reported nominal post-renovation value of 75 mm H_2O. The corresponding results for the selected manual keys are presented in Figs. 20–24.

With the blower switched off, the wind chest is unpressurized. Under these conditions, depression of key 1 (Fig. 9) transmits motion through the mechanical transmission elements 2–8 to the pallet valve 9. The measured key actuation force is then associated predominantly with the mechanical resistance of the key action and the restoring force of the pallet spring. With the blower operating, the wind chest is supplied with air at the reported nominal pressure of 75 mm H_2O (approximately 735 Pa). The pressure difference acting across the pallet valve produces



(a) (b)

(c) (d)

Fig. 18. Examples of repairs to the mechanical key action during the 2024 renovation: (a), (d) repair and adjustment of tracker components, (b) repair of the manual keys and their bearing components, (c) repair of square bearing components

an additional aerodynamic force opposing its opening. This force is transmitted through the mechanical key action to the manual key and consequently increases the force required to initiate pallet-valve actuation.

In a slider wind chest, the pallet valves control the admission of pressurized air to the corresponding tone channels. The dimensions of the pallet valves are related to the airflow demand of the pipes. Lower-pitched pipes generally require greater airflow and are therefore supplied through larger pallet valves. Towards the higher notes of the manual compass, the dimensions of the pipes and their airflow demand decrease, allowing smaller pallet valves to be used (Fig. 19). Since the aerodynamic force acting on a closed pallet valve depends on the wind pressure and the effective area exposed to that pressure, larger pallet valves are subjected to a greater aerodynamic load at the same wind pressure. Consequently, the contribution

of wind pressure to the key actuation force is generally greater for lower notes and decreases towards higher notes as the effective pallet-valve area becomes smaller.



Fig. 19. Pallet valves of the slider wind chest showing a gradual decrease in dimensions towards the higher notes

In addition to the pallet-valve dimensions, the stability of the wind supply may also affect the aerodynamic loading of the key action. The relatively small capacity of the wind reservoir may influence the operating conditions of the instrument, particularly when large chords are played, and several pipes require wind simultaneously. If the increased airflow demand temporarily exceeds the ability of the wind system to maintain the nominal pressure, a short-term decrease in wind pressure may occur. Such pressure fluctuations may affect both the airflow supplied to the pipes and the aerodynamic force acting on the pallet valves. Consequently, the stability of the wind supply is an important factor in maintaining stable operating conditions of both the pipework and the mechanical key action.

Fig. 20 presents the mean key actuation forces measured for selected keys in the first manual octave after the 2024 renovation under unpressurized and pressurized conditions. The increase in key actuation force associated with the presence of wind pressure ranged from 1.0 N for the C♯ key to 1.9 N for the E key. The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition ($n = 10$).

Fig. 21 presents the mean key actuation forces measured for selected keys in the second manual octave with the wind chest unpressurized and pressurized. The increase in key actuation force associated with the presence of wind pressure ranged from 0.9 N for the e key to 1.6 N for the b key. The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition ($n = 10$).

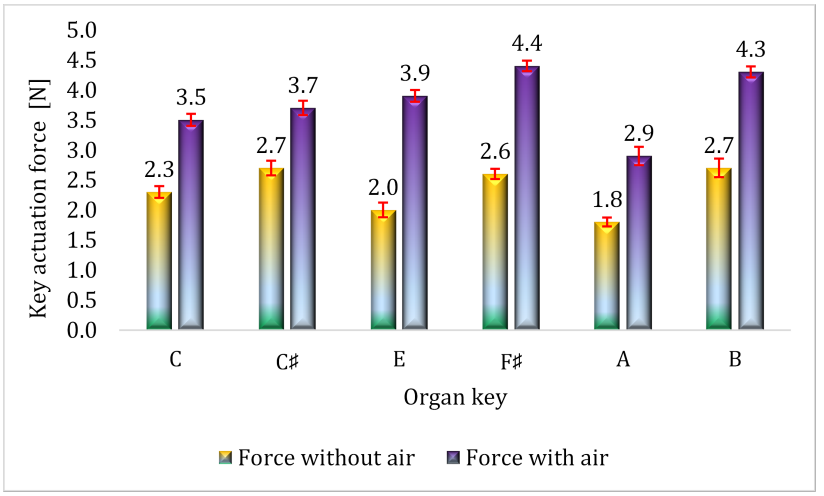


Fig. 20. Key actuation force for selected keys in the C–c octave under unpressurized and pressurized conditions (mean ± SD, n = 10)

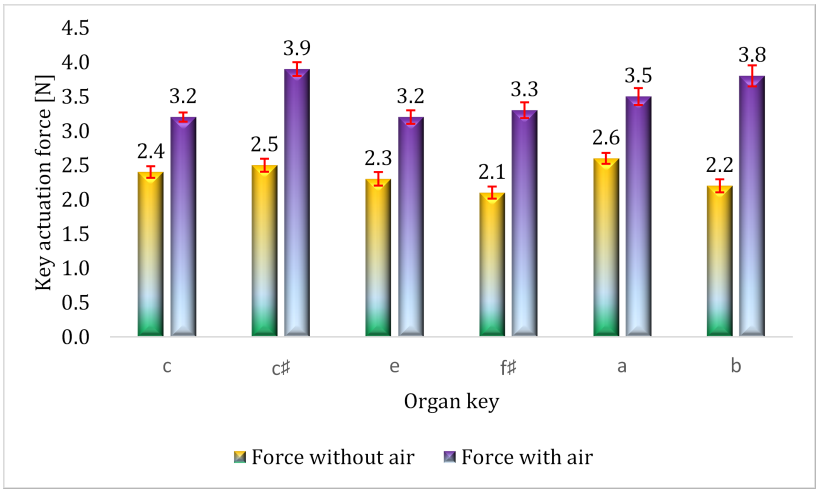


Fig. 21. Key actuation force for selected keys in the c–c^1 octave with the wind chest unpressurized and pressurized (mean ± SD, n = 10)

Fig. 22 presents the mean key actuation forces measured for selected keys in the third manual octave with the wind chest unpressurized and pressurized. An increase in the mean key actuation force was observed for all investigated keys when the wind chest was pressurized. The increase ranged from 0.4 N for the e^1 and a^1 keys to 0.7 N for the c♯^{1} key, demonstrating that the contribution of wind pressure to the key actuation force varied across the investigated keys. The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition (n = 10).

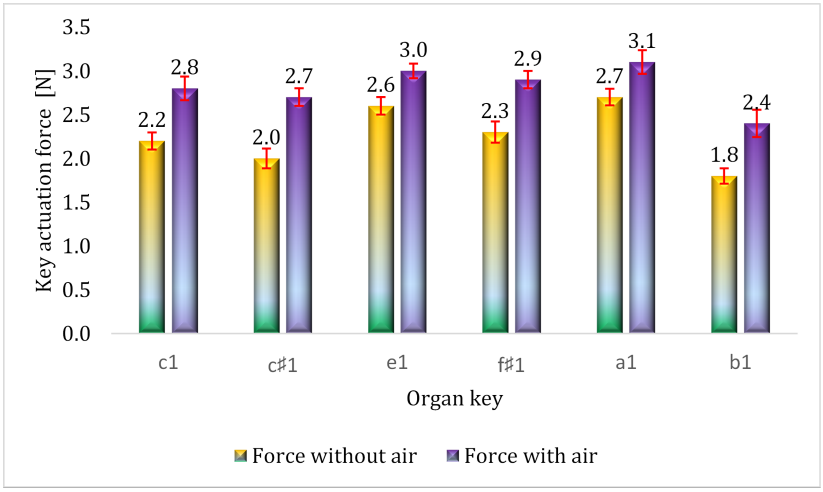


Fig. 22. Key actuation force for selected keys in the c^1–c^2 octave with the wind chest unpressurized and pressurized (mean ± SD, n = 10)

Fig. 23 presents the mean key actuation forces measured for selected keys in the fourth manual octave with the wind chest unpressurized and pressurized. An increase in the mean key actuation force was observed for all investigated keys when the wind chest was pressurized. The increase ranged from 0.2 N to 0.4 N, indicating a smaller contribution of wind pressure to the key actuation force than in the lower manual octaves. This result follows the general tendency observed across the manual compass and is discussed further below in relation to the dimensions

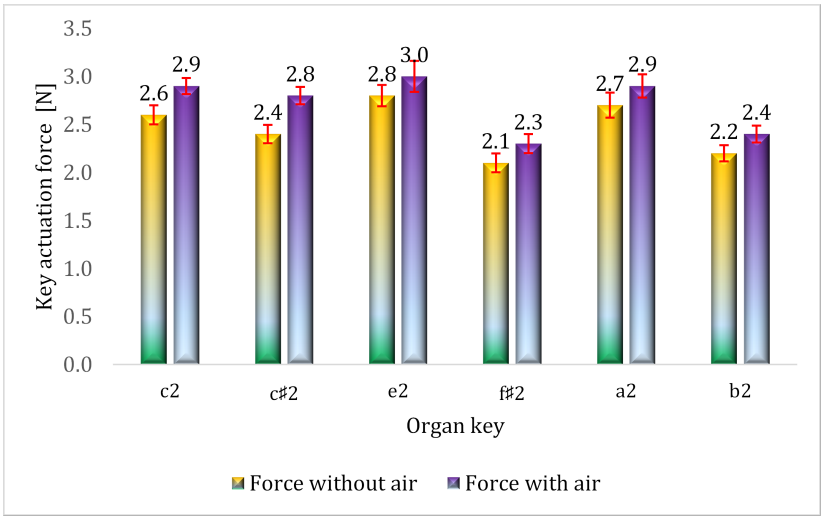


Fig. 23. Key actuation force for selected keys in the c^2–c^3 octave with the wind chest unpressurized and pressurized (mean ± SD, n = 10)

of the pallet valves. The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition (n = 10).

As shown in Fig. 24, the increase in mean key actuation force associated with wind pressure decreases to approximately 0.1 N in the highest section of the manual compass (c^3–f^3). This tendency is consistent with the progressively smaller dimensions of the pallet valves towards the higher notes (Fig. 19). The smaller pipes in this part of the compass require less airflow and are therefore supplied through smaller pallet valves [32]. Consequently, the effective pallet area exposed to wind pressure is reduced, resulting in a lower aerodynamic load at the same wind pressure. Since the observed difference of approximately 0.1 N is comparable to the measurement accuracy of the force gauge (better than ±0.1 N), this result should be interpreted with caution. The error bars represent the standard deviation of ten repeated measurements for each key and measurement condition (n = 10).

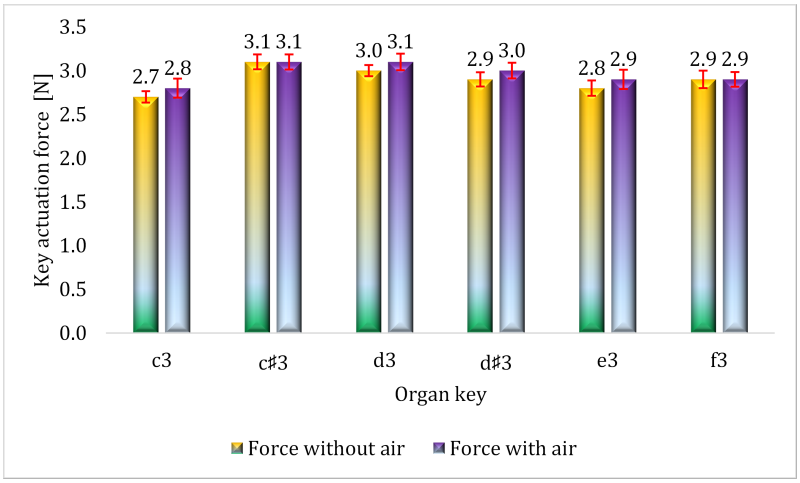


Fig. 24. Key actuation force for selected keys in the c^3–f^3 range with the wind chest unpressurized and pressurized (mean ± SD, n = 10)

An alternative pallet-valve design intended to reduce the influence of wind pressure on the mechanical key action was described by Audsley [1]. Its operating principle is illustrated in Fig. 25. During key depression, the auxiliary valve section (B) opens first against the restoring force of spring F [1–3]. This initial opening allows the pressure acting across the main pallet to be partially equalized before the main section of the valve is opened. As a result, the aerodynamic load opposing the opening of the main pallet is reduced, and a smaller proportion of this load is transmitted through the mechanical action to the key.

From a mechanical perspective, this design modifies the force conditions during pallet opening by reducing the direct influence of wind pressure on the main pallet. In a conventional pallet arrangement, the aerodynamic load depends on the

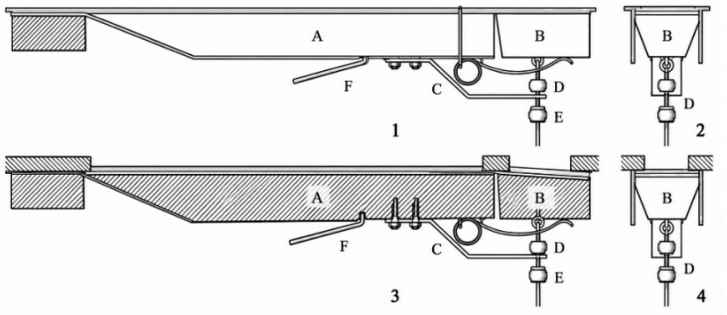


Fig. 25. Double-function pallet valve. Author's own elaboration based on [1].
A – main pallet valve; B – auxiliary valve section actuated first; C – fixed support controlling the auxiliary valve section; D, E – adjusting nuts; F – pallet spring; G – tracker connection; 1, 3 – side views of the valve mechanism; 2, 4 – corresponding transverse views

wind pressure and the effective pallet area, and this load contributes to the key actuation force. The auxiliary valve described by Audsley reduces this pressure-dependent component before the main pallet opens. The resulting force characteristic, however, also depends on the geometry of the key action, the pallet and spring arrangement, and the mechanical resistance of the transmission components [8, 16, 17]. Therefore, the effect of the valve design is considered here in terms of its influence on the mechanical and aerodynamic loading of the key action rather than in terms of playing comfort or keyboard ergonomics.

A separate series of measurements was performed to evaluate the additional mechanical loading introduced by the manual couplers. The investigated instrument is not equipped with pneumatic assistance, such as a Barker lever, or with electromechanical key assistance. Consequently, when a manual coupler is engaged, the key operates additional elements of the mechanical action, and the resulting additional resistance contributes directly to the force required to actuate the key [1, 2, 17].

Measurements with the super-octave coupler engaged were performed using selected keys from the $f\sharp^1$–$f\sharp^2$ and $f\sharp^2$–$f\sharp^3$ ranges of the manual compass. Corresponding measurements with the sub-octave coupler engaged were performed using selected keys from the b–b^1 and c–c^1 ranges. These measurements were used to quantify the additional mechanical loading introduced by the respective coupler mechanisms. The experimental results are presented in Figs. 26 and 27.

As shown in Fig. 26, engagement of the super-octave coupler resulted in a substantial increase in key actuation force. The coupler mechanically connects keys separated by one octave, so that depression of a single key simultaneously actuates the corresponding coupled key through the mechanical transmission system. As noted above, the investigated organ is not equipped with pneumatic assistance, such as a Barker lever, or with electromechanical key assistance [1, 2, 21]. Consequently, the additional mechanical resistance introduced by the coupled action is transmitted directly to the actuated key. The maximum key actuation force measured with the super-octave coupler engaged was 7.6 N.

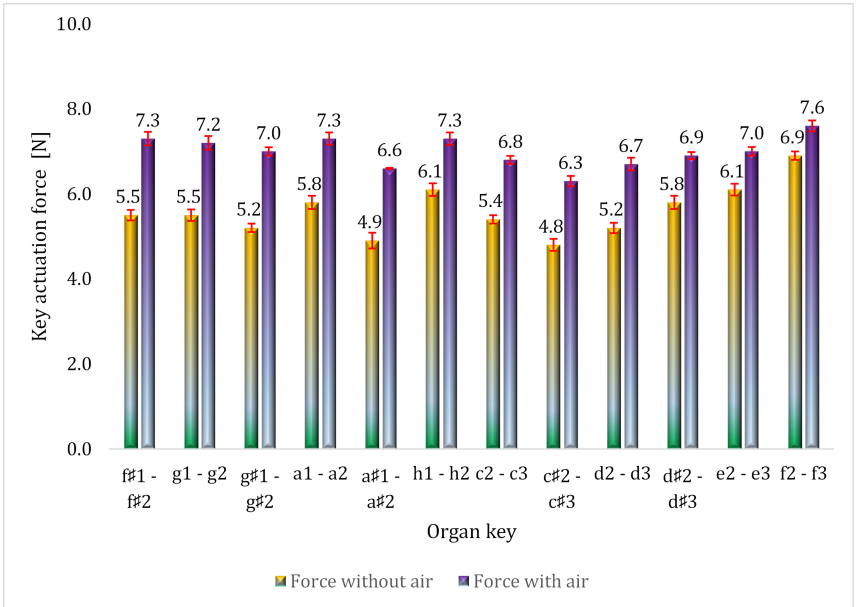


Fig. 26. Key actuation force with the super-octave coupler engaged (mean ± SD, n = 10)

From a mechanical perspective, engagement of the super-octave coupler introduces additional loading into the tracker action because the movement of one key must operate the mechanical transmission associated with the coupled key. Consequently, the measured force includes the resistance of the primary key action together with the additional mechanical resistance introduced by the coupled mechanism.

An even greater increase in key actuation force was observed with the sub-octave coupler engaged (Fig. 27). Under these conditions, the maximum measured force reached 9.4 N. As in the case of the super-octave coupler, this increase results from the additional mechanical loading introduced by the coupled action. Because no assisting mechanism is present, this additional load is transmitted directly through the mechanical key action.

Comparison of the wind-pressure and coupler measurements demonstrates that these two factors contribute to the key actuation force through different mechanisms. In the post-renovation wind-pressure experiment (Figs. 20–24), the increase in key actuation force associated with pressurization of the wind chest ranged from approximately 1.9 N for the E key in the lowest investigated octave to approximately 0.1 N for the c♯^{3} key in the highest investigated range. The decreasing contribution of wind pressure towards the higher notes is consistent with the progressively smaller effective area of the pallet valves (Fig. 19), which reduces the aerodynamic load acting on the valves at the same wind pressure.

In contrast, engagement of the manual couplers (Figs. 26 and 27) introduces additional mechanical loading by connecting the key to another part of the tracker

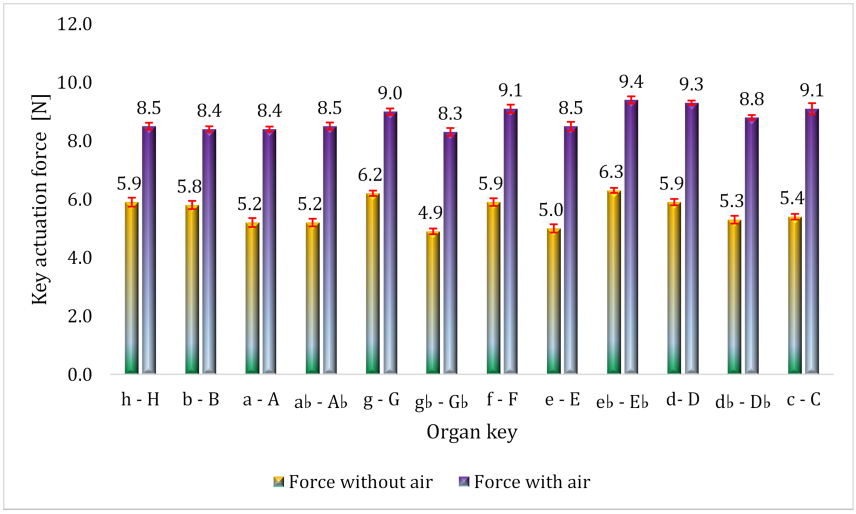


Fig. 27. Key actuation force with the sub-octave coupler engaged (mean ± SD, n = 10)

action. The maximum key actuation forces measured with the super-octave and sub-octave couplers engaged were 7.6 N and 9.4 N, respectively. These values demonstrate that, under the investigated conditions, the mechanical loading associated with the manual couplers produced a substantially greater increase in key actuation force than the aerodynamic contribution associated with wind pressure alone.

The experimental results, therefore, demonstrate that the key actuation force in the investigated tracker-action organ is influenced by both aerodynamic and mechanical factors. Separate measurements under unpressurized, pressurized, and coupled conditions make it possible to distinguish the contribution associated with wind pressure from the additional mechanical loading introduced by the manual couplers. In this context, the key actuation force provides a useful quantitative parameter for characterizing the operating conditions of the mechanical key action and for assessing changes in its mechanical loading.

5. Summary and conclusions

The investigation of the mechanical tracker-action pipe organ in St. Lawrence's Church in Nowy Sącz-Biegonice demonstrated that key actuation force can provide a useful quantitative parameter for characterizing changes in the mechanical condition of the key action. The study combined kinematic analysis with repeated force measurements performed before and after the comprehensive renovation completed in 2024.

The principal pre- and post-renovation comparison was conducted under identical unpressurized conditions, with the blower switched off, thereby isolating changes in mechanical resistance from aerodynamic loading. The maximum key

actuation force decreased from 4.5 N before renovation to 2.3 N after renovation, corresponding to a reduction of 2.2 N. This reduction primarily reflects changes in the mechanical resistance of the key action associated with the renovation.

Wind pressure was investigated separately after renovation. Pressurizing the wind chest to the reported nominal value of 75 mm H_2O increased the key actuation force by up to 1.9 N. This contribution generally decreased towards the higher notes, consistent with the progressively smaller effective area of the pallet valves. In the highest investigated range, the increase was approximately 0.1 N and therefore comparable to the accuracy of the force gauge, requiring cautious interpretation.

Manual couplers produced substantially greater mechanical loading. The maximum key actuation force reached 7.6 N with the super-octave coupler and 9.4 N with the sub-octave coupler engaged. Since the instrument has no pneumatic or electromechanical key assistance [1, 2, 21], the additional resistance introduced by the coupled actions is transmitted mechanically to the keys. Under the investigated conditions, coupler loading was therefore considerably greater than the contribution of wind pressure alone.

The kinematic analysis showed that both the key and stop actions are single-degree-of-freedom mechanisms according to the Chebyshev–Grübler–Kutzbach criterion. This analysis characterizes their kinematic structure and mobility, but does not determine the forces acting within the mechanisms and was therefore not used to calculate the key actuation force.

The reported nominal wind pressures of approximately 65 mm H_2O after the 2007 renovation and 75 mm H_2O after the 2024 renovation were obtained from the organ builders and were not independently verified. They should therefore be regarded as technical information characterizing the operating states of the instrument rather than measurements performed in the present study. Importantly, the difference between these values did not affect the principal pre- and post-renovation comparison, which was conducted with the wind chest unpressurized.

The results demonstrate that key actuation force measurements can quantitatively document changes in the mechanical condition of the same historical tracker action before and after renovation. Separating mechanical resistance from the additional effects of wind pressure and manual couplers is an important feature of the adopted methodology. Key actuation force may therefore serve as a supplementary diagnostic parameter for evaluating the condition of tracker actions and the effects of maintenance and renovation.

The study has several limitations. The measurements characterize the force required to initiate key-action movement and do not describe the complete force–displacement relationship or provide a complete assessment of keyboard toucher and playing ergonomics. The investigation was limited to a single historical instrument, and wind pressure was examined only after renovation. Furthermore, transient wind-pressure variations during operation were not measured [33], and the relatively small capacity of the existing wind reservoir may warrant further investigation under high airflow demand.

Future studies should include direct wind-pressure measurements using a documented procedure, force–displacement measurements throughout the complete key travel, measurements of transient wind-pressure variations under different operating conditions, and investigations of tracker-action instruments with different mechanical configurations. Such measurements may complement conventional organ-building inspection and documentation methods [34] and support the maintenance, conservation, and renovation of historical mechanical tracker-action pipe organs.

References

[1] G.A. Audsley. *The Art of Organ-Building: A Comprehensive Historical, Theoretical, and Practical Treatise on the Tonal Appointment and Mechanical Construction of Concert-Room, Church, and Chamber Organs*, Vols. 1–2. Dover Publications, New York, 1965. ISBN 0-486-21315-3.

[2] T. Kądziołka, S. Kowalski, and T. Mońko. Pipe organ evolution: From mechanical to mechatronical subsystems. *Journal of Engineering, Energy and Informatics*, 1:29–42, 2021.

[3] B. Konoval. Pythagorean pipe dreams? Vincenzo Galilei, Marin Mersenne, and the pneumatic mysteries of the pipe organ. *Perspectives on Science*, 26(1):1–51, 2018. doi: 10.1162/POSC_a_00266.

[4] P. Kowol, P. Nowak, and G. Lo Sciuto. A control strategy for mechatronic action of a pipe organ using a VCM actuator. *Electronics*, 12(23):4754, 2023. doi: 10.3390/electronics12234754.

[5] P. Kowol, P. Nowak, W. Banaś, and G. Lo Sciuto. Innovative design technologies of a miniaturized organ instrument. *International Journal on Interactive Design and Manufacturing*, 16:1551–1558, 2022. doi: 10.1007/s12008-022-00853-w.

[6] S. Kowalski, M. Pexa, Z. Aleš, and J. Čedík. Failure analysis and the evaluation of forced-in joint reliability for selected operation conditions. *Coatings*, 11(11):1305, 2021. doi: 10.3390/coatings11111305.

[7] S. Matthew. *Guidelines for the Installation and Maintenance of Pipe Organs*. Office of Liturgy, Archdiocese of New York, Yonkers, NY.

[8] A.G. Woolley. *The Physical Characteristics of Mechanical Pipe Organ Actions and How They Affect Musical Performance*. Ph.D. thesis, The University of Edinburgh, Edinburgh, UK, 2006.

[9] P. Domenighini and C. Buratti. The influence of thermal-hygrometric properties of air on the tune of pipe-organs. *Applied Acoustics*, 213:109611, 2023. doi: 10.1016/j.apacoust.2023.109611.

[10] N.M. Nagy. *Modeling the Sound Production of a Novel Organ Pipe Construction with Free Reed*. Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Budapest, Hungary, 2016.

[11] C.M. Oertel and A. Richards. Music and materials: Art and science of organ pipe metal. *MRS Bulletin*, 42(1):55–61, 2017. doi: 10.1557/mrs.2016.294.

[12] N. Macchioni, S. Lazzeri, L. Sozzi, and N. Puccini. Wood identification of the wooden components of a 19th century pipe organ. *Pro Ligno*, 15(4), 2019. ISSN 2069-7430.

[13] D.T. Węgrzyn, P. Wrzeciono, and A.A. Wieczorkowska. Predictive algorithms for determining blowing pressure in a pipe organ. *Bulletin of the Polish Academy of Sciences Technical Sciences*, 74(1):e156771, 2026. doi: 10.24425/bpasts.2025.156771.

[14] D. Węgrzyn, P. Wrzeciono, and A. Wieczorkowska. The reconstruction of blowing pressure in pipe organ using machine learning. In B. Marcinkowski, A. Przybyłek, A. Jarzębowicz, N. Iivari, E. Insfran, M. Lang, H. Linger, and C. Schneider, editors, *Harnessing Opportunities: Reshaping ISD in the Post-COVID-19 and Generative AI Era (ISD2024 Proceedings)*. University of Gdańsk, Gdańsk, Poland, 2024. doi: 10.62036/ISD.2024.113.

[15] P. Wrzeciono. Pattern recognition in music on the example of reconstruction of chest organ from Kamień Pomorski. *Sensors*, 21(12):4163, 2021. doi: 10.3390/s21124163.

[16] E. Asutay. *Physical Measurements and Subjective Characterization of Pipe Organ Mechanical Key Actions*. Licentiate thesis, Department of Civil and Environmental Engineering, Division of Applied Acoustics, Chalmers University of Technology, Technical Report No. Lic 2013:4, Gothenburg, Sweden, 2013. ISSN 1652-9146.

[17] A. Woolley. Mechanical pipe organ actions and why expression is achieved with rhythmic variation rather than transient control. In *Proceedings of the International Symposium on Musical Acoustics (ISMA 2010)*, pages 1–7, Sydney and Katoomba, Australia, 25–31 August 2010.

[18] B. Kostek. Articulation-related features in the pipe organ sound. *Archives of Acoustics*, 22(3):219–244, 1997.

[19] P. Pasternak. *Organs and Their Builders in the Sącz Region*. Mayor of the City of Nowy Sącz, Nowy Sącz, Poland, 2018 (in Polish).

[20] W. Witowski. *An Outline of the History of St. Lawrence Parish*. Redemptorist Little Printing House Publishing House, Tuchów, Poland, 2014. ISBN 978-83-7631-531-7 (in Polish).

[21] M. Wyszogrodzki. *Organ Construction*. Salesian Schools of Music, Lutomiersk, Poland, 2013 (in Polish).

[22] J. Erdman. *Organs: A Guide for Users*. Warsaw Archdiocese Publishing House, Warsaw, 1989. ISBN 83-85015-93-0 (in Polish).

[23] J.W. Hinton. *Organ Construction*. The Composers' and Authors' Press, London, 1900.

[24] P. Bordoni, P. Odya, J. Kotus, and B. Kostek. Sounding mechanism of a flue organ pipe – A multi-sensor measurement approach. *Sensors*, 24(6):1962, 2024. doi: 10.3390/s24061962.

[25] J. Haward. *Inside a Pipe Organ: Centuries Old Engineering with Wood, Wire and Leather*. National Lottery Heritage Fund, 2020.

[26] J. Angster, P. Rucz, and A. Miklós. Acoustics of organ pipes and future trends in the research. *Acoustics Today*, 13(1):10–20, 2017.

[27] C.E. Pykett. Pipe organs: Physics in an action. *Physics World*, December 2002.

[28] A. Gronowicz. *Fundamentals of Analysis of Kinematic Systems*. Wrocław University of Science and Technology Publishing House, Wrocław, 2003 (in Polish).

[29] D.B. Marghitu. *Kinematic Chains and Machine Components Design*. Elsevier Academic Press, Burlington, MA, 2005. doi: 10.1016/B978-0-12-471352-9.X5000-7. ISBN 0-12-471352-1.

[30] S. Miller. *Theory of Machines and Mechanisms: Analysis of Kinematic Systems*. Wrocław University of Science and Technology Publishing House, Wrocław, 1989 (in Polish).

[31] T. Młynarski, A. Listwan, and E. Pazderski. *Theory of Machines and Mechanisms. Part I: Synthesis and Structural Analysis of Mechanisms*. Cracow University of Technology Publishing House, Cracow, 1997 (in Polish).

[32] D. Węgrzyn, P. Wrzeciono, and A. Wieczorkowska. The dependence of flue pipe airflow parameters on the proximity of an obstacle to the pipe's mouth. *Sensors*, 22(1):10, 2022. doi: 10.3390/s22010010.

[33] J.L. Fischer. Shock wave characteristics in the initial transient of an organ pipe. In R. Bader, editor, *Computational Phonogram Archiving*, pages 269–304. Springer, Cham, 2019. doi: 10.1007/978-3-030-02695-0_13.

[34] N. Fredriksson, A. Åslund, and C.J. Bergsten. *Organ Documentation Manual*. Version 3.0. Göteborg Organ Art Center, Göteborg University, and Swedish National Heritage Board, Göteborg, 2005.